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SYNCHRONIZED VIBRATION GENERATORS FOR DYNAMIC TESTS OF FULL-SCALE STRUCTURES

by

D. E. Hudson

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A report of research carried out by the Earthquake Engineering Research Institute under State of California Standard Agreement No. 2163, for the State of California, Department of Public Works, Division of Architecture, Anson Boyd, State Architect.

Pasadena, California

November 1962

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SYNCHRONIZED VIBRATION GENERATORS FOR DYNAMIC TESTS OF FULL-SCALE STRUCTURES

Introduction. — The general considerations behind the design of a rotating weight sinusoidal vibration generator for dynamic studies of full-scale structures have been given in a previous report* which pointed out the advantages of a system of multiple synchronized machines that would permit a distribution of exciting forces throughout a structure so as to most efficiently excite various modes of vibration.

Under the sponsorship of the California State Division of Architecture a set of four synchronized vibration generators has been completed and tested, and the purpose of the present report is to summarize the design information on this new system, and to give detailed operating instructions for its use. (Fig. 1)

The design, development, test, and field application of this new system have involved the cooperative efforts of many people. The California State Division of Architecture, Anson Boyd, State Architect, has been represented throughout the project by Mr. J. F. Meehan, Research Director of the Schoolhouse Section, who has taken a keen interest in the program. Mr. C. M. Herd and Mr. Ernst Maag of the Division of Architecture have also closely followed the development of the project. The whole program has been under the direction of the Earthquake Engineering Research Institute, through a special committee consisting of Professors L.S. Jacobsen,

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* Hudson, D.E., "A New Vibration Exciter for Dynamic Test of Full-Scale Structures," Earthquake Engineering Research Laboratory, California Institute of Technology, September, 1961.

Stanford University, R. W. Clough, University of California, Berkeley, and G. W. Housner and D. E. Hudson of the California Institute of Technology. The mechanical design of the vibration exciter and drive unit was carried out at the California Institute of Technology by Professor D. A. Morelli, with the assistance of Mr. R. D. dePencier and Mr. Boris Auksmann. The electrical speed control and synchronization system was developed by Professor T. K. Caughey and Mr. R. V. Powell, with the assistance of Mr. R. J. Williams of the Caltech Dynamics Laboratory. An important part of the field testing and development work was under the supervision of Professor W. O. Keightley, on leave from Montana State College, with the assistance of Mr. Ilhan Gozaydin. Professor N. N. Nielsen, on leave from the University of Southern California, also contributed to the field application tests. Mr. R. K. Malhotra assisted with the stress analysis calculations. The services of Mr. D. W. Laird and Mr. F. L. MacDonald of the Caltech Mechanical Engineering Shop were invaluable in the construction and installation phases of the project. Transportation and installation of equipment for field tests was carried out by the Caltech Physical Plant Facilities, Mr. Wesley Hertenstein, Director, under the supervision of Mr. A. S. Hicks. The development of the system was much aided by the opportunities for field testing afforded by the Department of Water and Power of the City of Los Angeles, with the cooperation of Mr. S. B. Nelson, General Manager and Chief Engineer, and with the very able assistance of Mr. H. B. Hemborg, Principal Engineer, Major Project Design and Inspection, Water Engineering Design Division. Assistance with instrumentation in connection with field tests was given by Mr. W. K. Cloud, Chief of the

Seismological Field Survey, U. S. Coast and Geodetic Survey, and by Professor C. M. Duke and Mr. David Leeds of the University of California at Los Angeles.

Field Applications. — The development of the vibration generator system was much assisted by opportunities to use several of the units for tests under actual field conditions at a stage when this experience could be used for design modifications.

The first test of this type was of a concrete intake tower at Encino Dam*. Since that time, a second intake tower at Encino Dam, together with a connecting bridge, have also been tested. Other tests using single vibration generator units were made of soil conditions at a proposed factory site, and of the dynamic characteristics of a rocket engine test stand.

The first field test involving synchronized machines was made at the Dry Canyon Dam of the Department of Water and Power of the City of Los Angeles. In Fig. 2 can be seen two synchronized vibration generators mounted on a concrete slab cast on the crest of the earthfilled dam. In Fig. 3 are shown typical resonance curves obtained from the tests. The large number of closely spaced lightly damped resonant peaks observed in this earthfilled dam evidently offer attractive possibilities for detailed studies of the dynamic physical properties of such structures, and additional studies of this type are planned.

The experience with the vibration generators and control systems

*Keightley, W. O., Housner, G. W., and Hudson, D.E., "Vibration Tests of the Encino Dam Intake Tower," Earthquake Engineering Research Laboratory, California Institute of Technology, July, 1961.

under the relatively severe field conditions at Encino Dam and at Dry Canyon Dam have demonstrated that the equipment has a ruggedness and flexibility suitable to a wide range of structural dynamic investigations.

Mounting the Vibration Generator Units. — By a suitable adjustment of the roller chain drive the horizontal inertia force vector can be oriented in any direction with respect to the machine. The mechanical strength of the unit is greater in some directions than in others, and hence if maximum inertia forces are to be generated the machine should be oriented so that the resultant inertia force vector is parallel to the motor mounting base plate as shown in Fig. 4.

It is expected that the most usual application of the vibration generator will involve bolting it to a horizontal concrete slab, such as a floor slab in a building. A mounting bracket is supplied which can be bolted to the concrete slab, and which can also be used as a template for the location of the bolts. This mounting bracket is normally attached to the concrete slab by six 1-inch diameter coarse thread bolts approximately 5 inches long. Three-quarter or 7/8-inch diameter bolts are satisfactory if the maximum force potentialities of the machine are not to be used. It has been found that "Rawl Multi-Calk" expandable lead anchors are a convenient means of fastening the mounting bracket securely to the concrete. With this particular anchor, one threaded and two plain inserts per bolt have been found to give satisfactory results. The bolt tightness in these anchors should be checked after each hour or so of operation at high force levels, as the vibration forces may loosen up the connections in time.

If the surface on which the machine is mounted is uneven, it may be necessary to place some shims under the mounting bracket support plates. Care should be taken not to deform the mounting bracket in bolting it down as this might cause excessive mounting stresses in the frame of the vibration generator.

If a concrete floor slab or a suitable structural steel foundation is not available for mounting, a special concrete block should be cast for mounting purposes. A concrete foundation suitable for mounting four synchronized units is shown in Fig.5. A similar slab of one-half the area can be seen in Fig.2 as the foundation for the two synchronized units at the Dry Canyon Dam test. The concrete slab should be poured in intimate contact with a firm, well-consolidated soil. Otherwise soil compaction under the vibration conditions may result in a loosening of the foundation.

The screws which hold the motor mounting plate on the back of the vibration generator are tapped into the cast aluminum torque box, and care should be taken not to damage the threads, and to avoid excessive tightening stresses in these bolts.

As will be discussed in more detail in the section on mechanical design, the 5/16-inch diameter screws attaching the top and bottom wrought aluminum plates to the cast aluminum torque box are highly stressed elements. These heat-treated high-strength screws have been originally tightened at a torque of 17.0 ft.lb. If any of these screws work loose during operation, they should be tightened with a torque wrench, being sure that the torque does not exceed the 17.0 ft.lb., as the tightening stresses could easily become sufficiently large to cause failure.

Vibration exciter unit No. 1 with the lead counterbalance weights should be mounted on its own special mounting bracket, which differs from the three other mounting brackets for the identical units Nos. 2, 3, and 4. This special mounting bracket for the counterbalanced unit includes special strengthening elements necessary to develop the full strength of the vibration generator frame.

The chains on the chain-drive sprockets should be brought up fairly tight by means of the adjustable idler sprocket. The chains should be checked occasionally, as the spring keeper on the removable link has a tendency to work loose. In dusty or sandy locations care should be taken to avoid too much grease or oil on the chains and sprockets, as otherwise a considerable amount of dirt will collect and damage the drive.

The vibration generators should never be run without an operator in a position to shut down the power within sight of the machines at all times. Periodic careful inspections should be made to note any loose screws or evidence of any overstress.

Inertia Force Magnitudes. — The output inertia force of the vibration generator unit depends upon the WR (lb.in.) eccentricity of the baskets and of the lead weights, and on the speed of rotation. For one unit, the magnitude of the sinusoidally varying inertia force is given by the expression:

$$\text{Inertia force in pounds} = (0.102)(\text{WR lb.in})(\text{ n rev./sec})^2$$

Two different configurations are involved. Unit No. 1 has counterbalanced baskets, and hence only the (WR) values of the lead weights need be considered in determining the output force. The force-speed relationships for this counterbalanced unit No. 1 are given in Fig. 6 for representative lead weight combinations. If other combinations of weights are used, the above formula, together with the (WR) values from Table I can be used.

Units 2, 3 and 4 are not counterbalanced, so the (WR) values of the baskets themselves must be added to those of the lead weights. This has been done in Fig. 7, which gives representative force-speed values for the non-counterbalanced machines. The (WR) values from Table I, together with the above formula, can be used for other combinations.

The curves of Fig. 7 have been calculated for a basket (WR) of 520 lb.in. which is the average value for units 2, 3 and 4. These average curves can be used if an overall accuracy of the order of 1 to 2% is sufficient. For more accurate work, forces should be calculated for the specific (WR) values, noting that the individual basket (WR) values are: No. 2, 538 lb.in.; No. 3, 510 lb.in.; No. 4, 518 lb.in.

The lead weights with the inserted folding rings are to be used with unit No. 1 (counterbalanced) only, and these weights are sufficiently uniform so that they can be used interchangeably in this one unit. The weights with the rings should not be used on the non-counterbalanced units No. 2, 3 and 4.

The three sets of lead weights with the inserted threaded lifting sockets are completely interchangeable within the three units.

In Fig. 8 is shown a diagram of the "exciter speed" voltmeter from the front panel of the control unit. Marked on this meter scale are voltage readings corresponding to the maximum permissible loads for various

TABLE I. UNBALANCED MOMENTS (WR) LB.IN.

Lead Weight Combination*	Counterbalanced** Weights Alone (Insert Ring)	Non-Counter-balanced Weights Alone (Insert Screw)	Non-Counter-balanced Weights Plus Baskets***
S1	455	427	947
S2	909	854	1374
S3	1365	1281	1801
S4	1818	1708	2228
L1	1415	1415	1935
L2	2830	2830	3350
L3	4245	4245	4765
L4	5660	5660	6180
S1 + L1	1870	1842	2362
S2 + L2	3739	3684	4204
S3 + L3	5610	5526	6046
S4 + L4	7478	7368	7888 (Max. WR)

* S2 = Two small weights, each basket
L1 = One pair large weights, each basket, etc.

** Counterbalanced to within 1/2% of single small weight WR.

*** Average (WR) of baskets for units 2, 3, 4 = 520 lb.in.

lead weight combinations. These limits combine the 5000 lb. load limit of Figs. 6 and 7 and the 18-volt per 1 cycle per second calibration of the standard tachometer system. This figure has been drawn for the non-counterbalanced units, and would be modified slightly for the counter-balanced unit.

Before operating the equipment, the limiting readings on the "exciter speed" meter as shown in Fig. 8 should be firmly fixed in mind, for the particular lead weight loads to be used.

Operating Instructions. — Before any electrical connections are made between the control unit and the mechanical vibration generator, check the mounting of the mechanical unit on the mounting bracket and foundation as discussed above to be sure the machine is firmly secured. Remove all of the lead weights from the baskets so that the initial tests can be made under minimum load conditions.

It should always be kept in mind that with the baskets loaded it may be possible to overspeed the unit, which under some conditions might lead to mechanical failure. For each lead weight load, consult Figs. 6, 7 and 8 for the limiting speeds.

Single Unit Operation. — For single unit operation the "master" control unit or any one of the "slave" units can be used. If the master unit is used, the 400-cycle per second power supply should be in the "off" position, and the three relative position error meters will be inoperative.

The four mechanical oscillators and control units are numbered, and if possible corresponding units should always be used together. If units are interchanged, some readjustment of the control system may sometimes be necessary, as covered in the section on multiple-unit operation.

When putting the equipment back in operation after field use, it is a good idea to check the cables for open connections and short-circuits prior to interconnecting the units.

For single unit operation,it is not necessary to use the contactor box (Fig. 14); the function of this box is to provide a means of shutting down the power to the whole system from any one of several synchronized units. If the contactor box is used with a single unit, however, the black adapter plug must be put in the "power out" receptacle on the back panel of the control unit (Fig. 11). For single unit operation, the receptacles "signal out", "signal in", "power out", and "synchro" on the back panel of the control unit (Fig. 11) do not need to be connected.

1) Before applying power to the control unit, remove the side panel from the unit, and remove the cover from the amplidyne control amplifier so that the position of the controls can be checked (Fig.13). These control readings should be: "Limit Control 2" = 10; "Limit Control 1" = 10; "Antihunt" = 10; "Balance" = 5; "Stability" = 0; "I.R.Drop Comp." = 0. Visually check the amplifier unit to see that all tubes are properly seated in their sockets, and that components and wiring are intact. The "remote-local" switch on the front panel (Fig. 9 or 10) should be put in the "local" position.

2) The "Power in" receptacle on the back of the control unit (Fig. 11) should be connected to a 220-volt, 3-phase A.C. supply with the 4 conductor power cable. A minimum capacity of 5 KW should be available for each unit. It is necessary to be sure that the power connection is made with correct phase sequence — this can be checked in two ways:

(a) A special phase sequence box has been provided (Fig.14). When this box is plugged into the supply line, one of the neon indicator lights will glow, indicating the receptacle which will give correct phase sequence.

(b) If the special phase sequence box is not available, remove the side panel from the control unit, and remove the small plate which covers the commutator at the left end of the amplidyne unit (Fig.12). While observing the commutator, push the start and stop buttons on the amplidyne control switch in rapid sequence, and observe if the direction of rotation agrees with the arrow marked on the amplidyne nameplate. If the speed is reversed, interchange any two of the 3 phase leads in the connecting plug, noting that the neutral pin is of a different shape than the 3 phase lead pins. Operation of the amplidyne unit for any appreciable period of time in the reversed rotation direction will damage the machine.

3) Interconnect control unit and motor with the 8 conductor motor cable, connecting 8-pin receptacle marked "motor" on the back of the control unit (Fig. 11) to the motor (Fig. 15). The cables furnished are 25 ft. in length. Longer cables may be used, however the length should be limited to 100 ft.

4) With the power off, rotate the baskets of the mechanical oscillator unit by hand counter-clockwise as viewed from the top, and observe the left-hand meter on the front of the control unit marked "exciter speed" (Fig. 9 or 10). Check for positive deflection of the exciter speed meter. This checks the continuity and polarity of the tachometer circuit.

5) With the A.C. power on, but the amplidyne off, turn on the "reference power supply" (Fig. 9 or 10) by first switching on the filament switch, and then after 30 seconds switching on the D.C. supply. Check this reference power supply by changing the setting of the "speed control" knob through its complete range noting that a corresponding reading appears on the right-hand meter marked "reference load" on the front panel of the control unit (Fig. 9 or 10). Set this "reference load" voltage to zero before starting the amplidyne.

6) Push amplidyne start button on "amplidyne control" on front panel of control unit. The amplidyne unit will then come up to its standard rotational speed. An internal time delay switch (30 seconds) delays power to the amplidyne electronic amplifier and to the motor field. After this time delay switch operates, the baskets on the mechanical oscillator unit will slowly start to creep around (in either direction) and the system is ready to operate.

7) At this point the relationship between the voltage reading on the "exciter speed" meter at the left side of the front panel (Fig. 9 or 10) and the speed of the baskets should be checked. This meter reads 0.1 volt per revolution per minute of the drive motor. The timing belt pulley gear ratio on the main drive and the chain sprocket teeth ratios are such that there is a three-to-one reduction in speed from the motor to the baskets. Thus with the standard set-up, one volt on the "exciter speed" meter corresponds to 3-1/3 rpm of the baskets, or 1 cycle/sec of the baskets corresponds to 18 volts on the meter.

The maximum permissible speed will depend upon the load of lead weights in the baskets as shown in Figs. 6, 7 and 8. The maximum meter readings corresponding to various typical load combinations are shown graphically in Fig. 8, which should always be checked for the appropriate load limit before beginning any test.

For more accurate speed readings the digital counter should be used. This counter is operated by a small permanent magnet generator which produces 100 pulses per revolution, and is driven at motor speed (Fig.15). The basket speed in revolutions per minute is obtained by dividing the digital counter reading by three hundred. Before proceeding with further tests, check the digital counter against the "exciter speed" meter to be sure that all conversion factors have been correctly applied.

As the speed approaches within 10% of that corresponding to the load limit, the speed should always be monitored by the digital counter.

8) With the system now in operating condition, slowly increase the speed control setting, observing that the baskets rotate counter-clockwise viewed from the top. As the speed slowly advances, note that the "exciter speed" meter tracks the "reference load" meter, i.e. , the tachometer output tracks the reference power supply reading. If these two meters cease proper tracking at any time, the control system is malfunctioning, and the whole system should be immediately stopped by pushing the "Amplidyne Control-Stop" button. If at any time the "exciter speed" meter reading exceeds the "reference load" meter reading while the speed is being increased, stop the system immediately, and determine the cause of the malfunction before restarting.

The system is now in proper operating condition for use. The rate at which speeds are changed should be limited to that which will keep the two meters suitably tracking.

9) To stop the system the preferred procedure is to reduce the speed control setting until the speed is practically zero, and then push the "Amplidyne Control-Stop" button. In emergencies, the speed control can be rapidly reduced to zero, thus introducing dynamic braking into the system. The unit can also be stopped from any speed by simply pushing the "Amplidyne Control-Stop" button. The mechanical oscillator will then coast to a stop, taking a somewhat longer time to do this than if the speed control had been rapidly decreased to zero before stopping the Amplidyne.

10) To start the unit again, assuming no alteration in the connections, repeat the above steps from item 6 on.

Note (1) – The equipment should never be operated without a continuous monitoring of the control panel. If any change occurs in the exciter speed meter reading without a corresponding adjustment having been made, or if the exciter speed and the reference voltage fail to track properly, the system should be immediately stopped by pushing the Amplidyne Control-Stop button.

Note (2) – If the basket rotation is not uniform, but is subject to a superimposed oscillation, i.e., "hunting", the settings of the two "limit controls" in the Amplidyne Amplifier (Fig.13) should be reduced an amount necessary to just eliminate the oscillation. This hunting will also be noticed as an oscillation of the exciter speed meter reading, and as a variable pitch in the Amplidyne sound.

Note (3) – Never switch off the "reference power supply" while the system is operating, and never disconnect any cables while the system is operating.

Note (4) – By pushing the "Amplidyne Control-Stop" button at the full speed operating condition, the unit will coast down to rest and can be used for "run-down" resonance tests. The rate of speed decrease, however, is such that important detail may sometimes be missed in the resonance curves, and such run-down tests are not recommended except in special circumstances.

Multiple Unit Operation. – As mentioned before, it is a good idea to check out all cables for continuity and short-circuits, particularly after the system has been used in the field. It is advisable to retain the numbered units in corresponding pairs. Study the above operating instructions for single unit operation thoroughly before attempting synchronized operation of multiple units.

1) Check the positions of the controls in the amplidyne amplifier (Fig.13) as in item (1) under "Single Unit Operation" above. Check that the 400-cycle per second power supply switch on the front panel of the master control unit is in the "off" position.

2) Interconnect control units with the power cables, joining the "power in" and "power out" receptacles on the back of the control units.

3) Connect power cable between the control unit nearest to the power source to the contactor box. (Fig.14)

4) Connect contactor box to 220 volts, three-phase A.C., observing correct phase sequence, as in item (2) under "Single Unit Operation" above.

5) Insert black adapter plug in the remaining unoccupied "power out" receptacle on the last control unit of the chain. This plug can be used as a safety lock for the system — with this plug removed no power can be applied to any part of the system.

6) Connect motor cables (8 conductor - 8 pin) between control units and mechanical oscillators.

7) The "remote-local" switch on each unit should be switched to the "local" position so that each unit can be checked individually before the synchronizing connections are made.

8) Push the "Generator Control-On" button on any one of the control unit front panels (Fig. 9 or 10) to activate the contactor box and apply power to all of the units. At any time the power can be shut down on all of the units by pushing the "Generator Control-Off" button on any unit.

9) With the power on, check each unit separately as in items (4) through (8) under "Single Unit Operation". Any individual unit can be stopped by pushing the "Amplidyne Control-Stop" button on that unit. By pushing the "Generator Control-Stop" button on any one of the units, all power will be cut off, and all units will stop.

10) Stop all units by pushing "Generator Control-Stop" button on any one of the units. Connect the synchronizing cables (9 conductor, 9 pin) between the "synchro" receptacle on the back of each unit, and the motor assembly unit (Fig. 15).

11) Interconnect all control units with the 9 conductor control signal cables between the 9 pin receptacles marked "signal in" and "signal out" on the back panel of each control unit.

12) Switch "on" the 400-cycle per second synchro power supply on the front panel of the master control unit (Fig. 9).

13) With the amplidyne power off and the 400-cycle per second power on, rotate the baskets of the "slave" units by hand and observe the corresponding deflections of the "relative position error" meters on the front panel of the master control unit (Fig. 9). With a 180° rotation of the basket, the meter reading should go through a maximum and back to a minimum. This checks the correct operation of the signal circuits. If the location of the master unit is such that it is not convenient to observe the "relative position error" meter while the slave basket is being rotated, the same error voltage reading can be obtained at the slave unit using the red and black terminals at the upper left panel of the slave unit (Fig.10). Any voltmeter, such as a Simpson 260 test meter on the 0-10 volts A.C. scale, can be used for this indication.

The orange and black terminals on the slave units (Fig.10) measure the 400-cycle per second control signal, which has been set at 6.5 volts, and should not require adjustment.

As a final check of the synchronizing circuits, swing the baskets on the master by hand and note that all three "relative position error" meters on the master control unit deflect appropriately.

14) Check that all timing-belts and roller chains are on the mechanical oscillator units in a proper orientation to give the desired direction of applied force. For an initial run, remove all lead weights from the baskets. Check that all mechanical units are securely bolted to the base plate and foundation, and that all nuts and bolts are tight.

15) To correctly phase the units, each slave unit should be individually adjusted as follows. Rotate the basket on the slave unit in a position in which the synchro shaft position adjusting screw (Fig.15) is accessible. Put the baskets of the master unit in the same position, and rotate the synchro shaft position adjusting screw until the "relative position error" meter on the master control unit or the corresponding voltmeter reading at the slave control unit reads a minimum near zero. This adjustment will insure that the master and slave are either in phase or 180° out of phase. To distinguish between these two positions the following procedure can be used:

(a) Put the "remote-local" switch on the front panel of the master and slave control units in the "remote" position. Slave units not being checked should be in the "local" position.

(b) Start the amplidynes in the master and slave units by pushing the "amplidyne control-start" button on the master control unit. This will start the amplidynes in the master unit and in any slaves in the "remote" position. Rotation of units will not start simultaneously because of differences in the individual time delay circuits. The speed control should not be advanced until all units have field voltage applied as evidenced by a slow rotation of the baskets.

(c) Using small adjustments of the speed control knob, put the baskets in the master unit in some convenient phase reference position, and note the corresponding alignment of the slave baskets. If the slave basket is 180° out of phase, push the amplidyne stop button on the master control unit, stopping both units. Put the slave and master baskets in the same phase position with the synchro adjusting screw in an accessible position and note that the "relative position error" meter reads near zero. Rotate the synchro adjusting screw in either direction until the meter goes through a maximum and back to a minimum near zero. This will shift the phase 180° thus synchronizing the two units.

16) Repeat the above synchronizing procedure for each slave unit to be used for the test.

17) If one or more of the "relative position error" meters show a fixed offset phase error with respect to the other machines, which increases with speed, a "static" adjustment of the system is needed to account for small differences in system characteristics. This will ordinarily not be required unless there has been an interchange of control units and mechanical oscillator units. For this reason it is advisable to use the units in numbered pairs. If necessary, this adjustment can be made as follows:

(a) Put master unit and slave to be checked on "remote", other slaves on "local". The units are assumed to be already synchronized as in item (16) above.

(b) Remove side panel from master control unit and locate potentiometer control "tachometer sensitivity adjustment" outside the right end of the amplidyne amplifier box, (Fig. 12). Set this control at mid-position.

(c) Start the amplidynes in the master and slave units, by pushing the "Amplidyne Control-Start" button on the master unit. As speed is increased note increasing offset error on the corresponding "relative position error" meter.

(d) Remove side panel from slave control unit and adjust "tachometer sensitivity adjustment" control until the relative position error is a minimum as indicated in the meter on the master unit, or by a voltmeter at the slave control unit.

(e) Repeat for all slave units needing offset error adjustment.

Note: — A more sensitive adjustment of the phase can be made by removing the timing belt from the mechanical oscillator unit so that the motors can be run at full speed. This should not ordinarily be necessary.

18) To run the units synchronously, put all control units on the "remote" position and switch "off" all slave reference power supplies. Remove all lead weights from the baskets. Start all amplidynes by pushing the "amplidyne control-start" on the master control unit. The units should now all run synchronously under the control of the "speed control" knob on the master control unit, as indicated by the "relative position error" meters. The system is now in operating condition. Observe the same precautions in tracking the "exciter speed" meter and the "reference load" meter as were mentioned above under item 8. If any "relative position meter" swings through large angles, that unit is not properly synchronized. If any meter shows an offset without swinging, that unit needs a static balance as described in item (17) above.

The whole system can be stopped by either (a) pushing the "amplidyne control-stop" button on the master control unit, or (b) pushing the "generator control-stop" button on any unit. Any slave unit can be individually stopped by pushing the "amplidyne control-stop" button on that slave unit. By putting the slave unit on "local" it will be removed from the system and will not operate. As in single unit operation, the system can be brought to rest most quickly by rapidly reducing the speed control knob to zero before cutting off the power.

Note (1) – The speed should be limited corresponding to the load by reference to Figs. 6, 7 and 8.

Note (2) – For synchronous operation, the positions of the two "limit controls" in the amplidyne amplifier to prevent hunting may be more critical than for single unit operation. The optimum setting of these controls will depend upon the total lead weight load in the baskets.

Note (3) – To run one individual unit only in a synchronized system of several machines, the following procedure can be used:

(a) To run the master unit separately – stop the system by pushing the "generator control-stop" button on any one of the units. Put all of the control unit "remote-local" switches on "local". Start the master unit by pushing the "generator control-start" button, and then the "amplidyne control-start". The 400-cycle per second synchro power supply on the master unit can be switched off.

(b) To run a slave unit separately – stop the system by pushing the "amplidyne control-stop" button on the master unit, or the "generator control-stop" button on any one of the units. Put the "remote-local" switches on all of the units in the "local" position. Switch on the "reference power supply" on the unit to be operated and check as above for single unit operation. The reference power supply and the 400-cycle per second synchro power supply on the master unit must be switched off. Start the slave unit to be operated by pushing the "generator control-start" button, and the "amplidyne control-start" button on the slave to be operated.

Note (4) Never switch off the "reference supply" on either the master or slave units while the system is operating. Never disconnect any cables while the system is operating or power is applied.

Note (5) Never operate the system without continuous monitoring of the "exciter speed" meter and the "reference load " meters. If there is any failure of the exciter speed meter and the reference load meter to track properly or any indication of loss of synchronization of any unit, the whole system should be immediately shut down by pushing the "generator control-stop" button on any unit.

Note (6) With the power cut off the units will not remain in synchronization while they are coasting to rest. The synchronized system thus cannot be used for "run-down" tests.

Speed Control and Synchronization System. — The basic elements of the speed control and synchronization system may be seen in Fig.16. Any one of the units enclosed in the large dashed rectangle may be used separately as a speed control for an individual vibration generator. The power for the 1-1/2 H.P.D.C. motor is obtained from a standard electronically controlled amplidyne unit. Connected to the drive motor shaft is a tachometer which produces a voltage proportional to the speed. This speed signal is compared with a fixed reference voltage, which can be adjusted to any value, and the difference between the reference voltage and the tachometer voltage is applied to the amplidyne control amplifier which then alters the drive speed to bring the velocity difference signal to zero.

For multi-unit synchronized operation, additional slave units are connected to a master control unit as shown in Fig.16. Each of these slave units has its own reference power supply so that it can be used as a complete speed control unit for individual drives. For synchronized operation, the reference power supplies in the slave units are switched off and all units are compared with the one master reference voltage source as indicated. By this means all of the units can be controlled to run at the same basic speed.

It will not be possible to maintain correct synchronization of the units by means of a speed control alone. Inevitable slight changes in the speeds of the individual units will lead to cumulative phase errors which cannot be permitted to occur. Position error control is thus required as well as speed control, and this is accomplished by means of selsyn units driven from the main drive motor shafts. A 400-cycle per second selsyn transmitter is attached to the master unit drive, and corresponding selsyn receivers are mounted on the slave unit drive motors. Each slave control unit contains a demodulator which produces a position error signal proportional to the difference between the angular shaft positions of the master and slave drive motor. This position error signal is then applied to the input of the amplydine amplifier, which operates to reduce the position error to a minimum.

In this way all units can be kept accurately in synchronism as the speeds of all of the units are varied by the single control on the reference power supply in the master unit.

The complete details of all electrical circuits are given in Figs. 17 through 21. Figure 17 is a block diagram of the whole system which is similar to Fig. 16 but which indicates in more detail the major controls. Figure 18 is a wiring diagram for the electronically controlled amplidyne, a standard General Electric Type 5AM-79AB334D unit with a Type 7513-K100-G1 Electronic control amplifier, with minor modifications as shown. In Fig. 19 are shown details of the connections for the generator control contactor box shown in Fig. 14, which permits control of main power to all control units from any one of the control units. In Fig. 20 are given the circuit details for the synchronizing system. The 400-cycle per second power supply is a standard Model 1301 unit manufactured by Communication Measurements Laboratory, Inc., and the reference power supply is a Lambda Electronics Corporation Type C-280. Figure 21 gives the circuit diagram for the de-modulator, one of which is included in each slave unit.

Mechanical Design Features. — Of the four mechanical rotating weight units, three are identical units, and one is the original prototype model which differs in the following respects from the later model:

1) Lead counterweights have been bolted to the baskets, so that with no lead weight inserts the unbalanced (WR) moment is essentially zero. This unit can therefore be used for smaller forces than can be obtained with the non-counterbalanced baskets alone.

2) A smaller size chain is used than on the modified machine. The sprockets were originally designed to take three parallel chains. This was found to be unnecessary, so a single chain is now used on the center sprockets.

3) The sprocket teeth ratios differ from those of the three newer units. The timing belt drive pulley ratios are also different, so that the overall speed ratio on all four machines is the same 3 to 1 ratio.

4) On the new machines, a strengthening cast aluminum torque box extension piece has been added to the torque box assembly. In place of this, the original counterbalanced machine has a special strengthened mounting bracket which should always be used. The mounting brackets for the three new machines are interchangeable.

5) The lead weights for the original counterbalanced machine have brass insert rings for handling instead of the inset threaded sockets in the weights for the new machines. The two knurled screws holding the protective cover over the timing belt main drive can be used with these threaded inserts to handle the lead weights. The brass ring weights can be used in any combination in the original unit only, and should not be used in the new machines. The threaded insert lead weights are completely interchangeable between any of the three new machines, and in any one unit.

The complete drawings of the mechanical elements of the latest model of the rotating weight mechanical units are included in the appendix to the figures at the end of the report.

<u>Stress Analysis of the Vibration Generator Mechanical Unit.</u> — In the course of the mechanical design of the vibration exciter, numerous calculations were made of stress conditions at various critical points. In addition, tests were made on the completed unit using wire strain gages and stress-coat techniques to verify the stress conditions in important elements. The maximum total inertia force limit of 5000 lb. has been based on these studies plus experience gained in the field under typical mounting conditions.

The 5/16-in. screws attaching the top and bottom plates to the torque box are critical elements in the design, and it is the stresses in these screws that governs the "stronger" and "weaker" orientation of the exciting force as shown in Fig. 4. As an example of the stress analysis calculations, the computations of the maximum stress conditions in these screws under the most unfavorable inertia force orientation will be given.

In Fig. 22 are shown the force diagrams and the essential dimensions for this calculation. The screws, which are distributed around the center line of the torque box, as can be seen in the detailed drawing of the top plate, are subjected to a combination of direct shear, torsional shear, tension, and a tightening axial load.

In Fig. 22 the rotating baskets are oriented so that the total inertia force F is perpendicular to the motor mounting plate, which will give the maximum combined stress in the screws. The orientation of the inertia force parallel to the motor mounting plate will result in lower stresses in the screws, and this orientation should always be used if high forces are to be generated.

The forces acting in the plane of the top and bottom plates may be calculated from the free-body diagram in the lower right corner of Fig. 22. Supposing that the maximum inertia force F is 5000 lb., and that the full load of lead weights is used so that $WR = 7888$ lb.in. (from Table I), we may take moments about the x-axis and obtain

$$\Sigma M_x = 0 = +R_{2y}(12.06 \text{ in}) + 7888 \text{ lb.in.} - (2500 \text{ lb})(12.06 \text{ in.})$$

$$R_{2y} = \underline{\underline{1844 \text{ lb.}}}$$

$$\Sigma F_y = 0 = R_{1y} + R_{2y} - 5000; \quad R_{1y} = \underline{\underline{3156}} \text{ lb.}$$

There are forty 5/16-in. screws each having a root area of 0.0454 in.^{2}. The direct shear acting on the torque box screws for the top plate will therefore be;

$$\tau_o = \frac{3156 \text{ lb.}}{(40)(0.0454 \text{ in.}^2)} = 1740 \text{ lb/in.}^2$$

Since the line of action of R_{1y} does not pass through the centroid of the area of the screw pattern, there will also be a torsional shear stress. Referring to Fig. 22, the moment M_z acting on the joint is

$$M_z = (R_{1y})(a) = (3156 \text{ lb.})(4.4)\text{in.}$$

The screw located at the maximum distance from the centroid is No. 2, at a distance of 18.16 in. If x_{ic} and y_{ic} are the coordinates of the individual screws referred to the centroid of the screw pattern, we have

$$\sum_{i=1}^{40} (x_{ic}^2 + y_{ic}^2) = 5254 \text{ in.}^2$$

The distances were measured graphically from the detailed drawing. The torsional shear stress on screw No. 2 is:

$$\tau_T = \frac{(R_{1y})(a)(b)}{A\sum_{i=1}^{40}(x_{ic}^2+y_{ic}^2)} = \frac{(3156\text{ lb})(4.4\text{in.})(18.16\text{ in.})}{(0.0454\text{ in.}^2)(5254\text{ in.}^2)}$$

$$\tau_T = 1060\ \frac{\text{lb}}{\text{in.}^2}$$

In screw No. 1, this torsional shear stress is:

$$\tau_T = \frac{(3156\text{ lb})(4.4\text{ in.})(15.26\text{ in.})}{(0.0454\text{ in.}^2)(5254\text{ in.}^2)} = 886\ \frac{\text{lb}}{\text{in.}^2}$$

There will also be a tension stress in the screws since there is a force tending to separate the top and bottom plates. The system is of course statically indeterminate, but because of the symmetry of the structure it is possible to get a simple approximation for the maximum possible moment $(M_x)_{T.B.}$ acting on the torque box screw system.

This maximum moment will be

$$(M_x)_{T.B.} = (3156\text{ lb.})(12.06\text{ in.}) = 38,000\text{ lb in.}$$

The maximum tension stress will be in screw No. 1, which is located at the maximum distance of 7.0 in. from the neutral axis which passes through the centroid of the screw pattern:

$$\sigma_{max} = \frac{Mc}{I} = \frac{(M_x)_{T.B.}(c)}{A\sum_{i=1}^{40} y_{ic}^2} = \frac{(38,000\text{ lb.in.})(7.0\text{ in.})}{(0.0454\text{ in.}^2)(453.4\text{ in.}^2)}$$

$$\sigma_{max} = 12,900\text{ lb/in.}^2$$

In the above calculation of σ_{max} the strengthening effects of the 3/4 in. diameter x 15 in. long through bolts have been neglected because the total elongation of these bolts is large compared to that of the screws. These through bolts could themselves take the whole tension load without being highly stressed, and they therefore act as a second line of defense to prevent any complete failure of the machine.

If we now compare the various stresses acting on the screws, it will be evident that because of the large tension force on screw No. 1, this screw will be the critical point. It will also be observed that the tension stress $\sigma = 12,950$ lb/in.^{2} is sufficiently large compared to the shearing stresses $\tau_D = 1740$ lb/in.^{2} and $\tau_T = 886$ lb/in.^{2} so that the maximum combined tension stress will not be much greater than this tension σ. We may thus conclude that the maximum stress in the screws under the worst loading condition corresponding to an inertia force output of 5000 lb is $\sigma_{max} \approx 13,000$ lb/in.^{2}.

This stress is sufficiently high so that a question exists as to the safety of the 5/16 in. screws, considering the fact that the initial tightening stresses may be large. It is desirable that the screws should be well tightened so that they will not work loose during operation, but it is well-known that it is easy to cause tension failures in such small screws by excessive tightening.

The tightening torque for the screws has been standardized as 17 ft. lb. According to information given in the book, Laughner, U.H. and Hargan, A.D., "Handbook of Fastening and Forming of Metal Parts," McGraw-Hill Book Co., Inc., N.Y., 1956, the axial load set up in a 5/16 in. 18 threads per inch screw is 16.6 lb. per lb. in. of tightening torque. This number must of course be subject to a wide variation depending upon the actual coefficients of friction existing in the threads and between the surfaces. Taking this as a representative value, however, the tension stress set up by the tightening would be:

$$\sigma_T = \frac{(17\ \text{lb.ft.})(12\ \text{in./ft})(16.6\ \text{lb/lb.in.})}{0.0454\ \text{in.}^2} = 74,500\ \text{lb/in.}^2$$

The original model of the machine at one time used ordinary low-carbon screw-stock screws, and none of the screws were broken off in tightening to the standard 17 ft. lb. torque or under test load. This suggests that the actual friction conditions in the cast 356T6 aluminum result in somewhat lower stresses than the above calculation indicates. In view of the possibility of the high tightening stress plus the additional significant tension stress under load, it was decided in the final design to use heat-treated high-carbon screws having a tension ultimate of some 120,000 lb/in.^{2}.

Tests were made of the strength of the threads in the cast aluminum, and it was found that a high-strength Allen-head screw could be tightened to the point of bending the Allen-head wrench without thread failure. It thus appears that tension in the bolt is the limiting factor rather than the strength of the aluminum threads even for the high-strength screws.

The 356T6 cast aluminum used in the torque box and in the rotating baskets has an ultimate strength of about 30,000 lb/in.^{2}. The design of the rotating baskets is governed mostly by geometry and considerations of casting requirements. The nominal stresses in the rotating baskets are low, and care was taken in the design to avoid stress concentrations.

<u>Compressional Stress in Top Plate</u>. — The compressional bearing stress in the 5/8 in. thick top aluminum plate can be calculated on the basis of projected area as:

$$\sigma_B = \frac{(3156 \text{ lb.})}{(1.5 \text{ in.})(0.625 \text{ in.})} = 3360 \text{ lb/in.}^2$$

The top and bottom plates are 6061 T6 wrought aluminum plates with a warranted ultimate tension stress of 40,000 lb/in.^{2}. It thus appears that the bearing stress and the direct tension stresses are not significant.

<u>Bearing Loads</u>. — The total maximum radial load on the taper roller bearings caused by the gravity moment with full baskets and the maximum 5000 lb. inertia force is 2310 lb. The 2.500 in. bore medium series taper roller bearings are rated at 500 rpm at a radial load of 3005 lb. Considering that a long service life at high speeds is not involved, the bearing loads are thus seen to be conservative.

FIGURE CAPTIONS

FIGURE CAPTIONS (Continued)

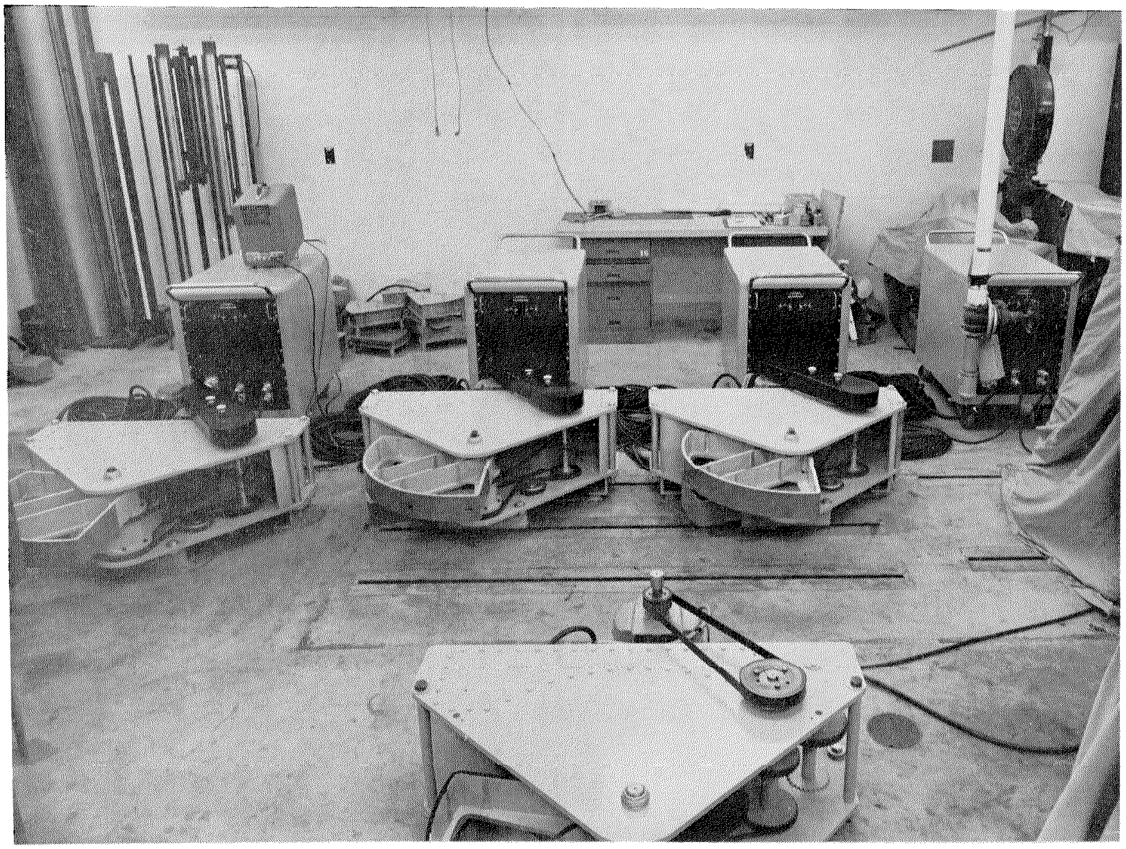


Fig. 1 General View of Four Vibration Generators and Control Assemblies During Synchronization Tests.

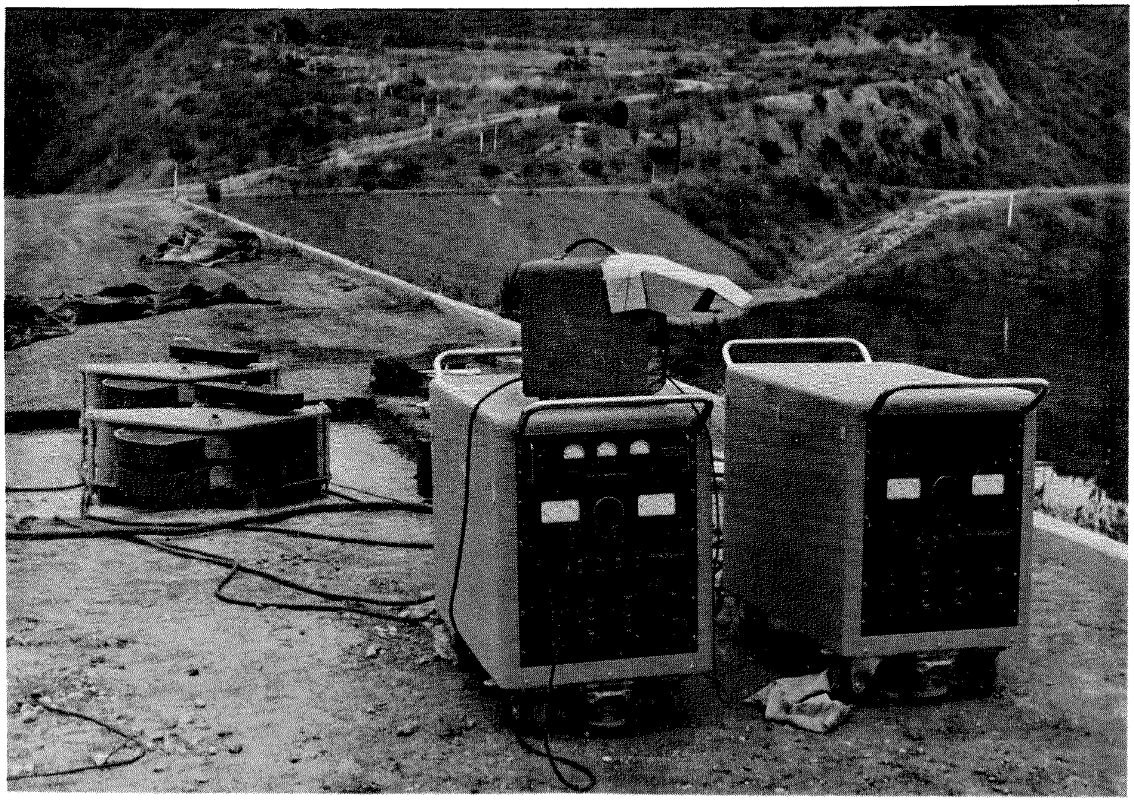


Fig. 2 Two Synchronized Vibration Generators at Dry Canyon Dam.

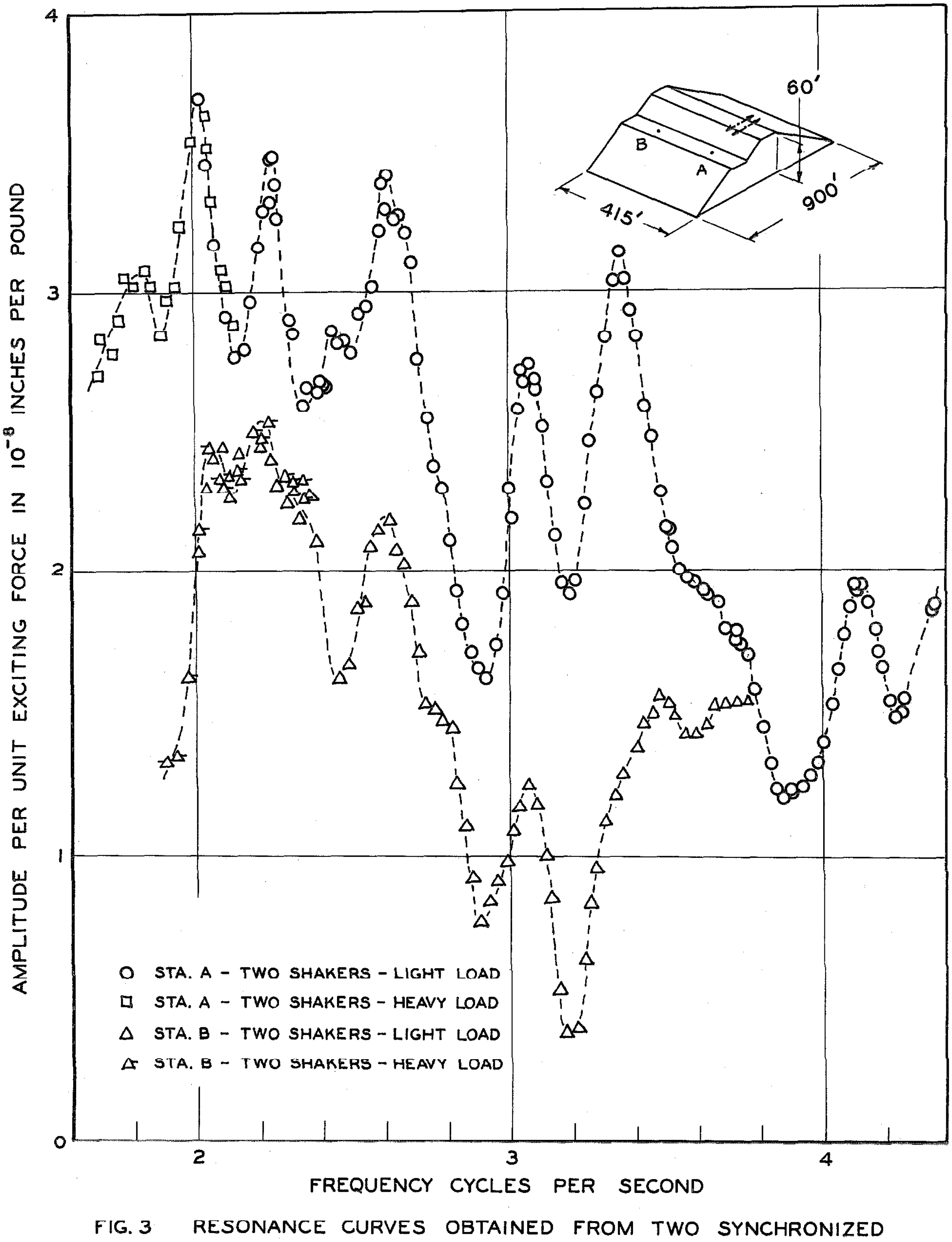
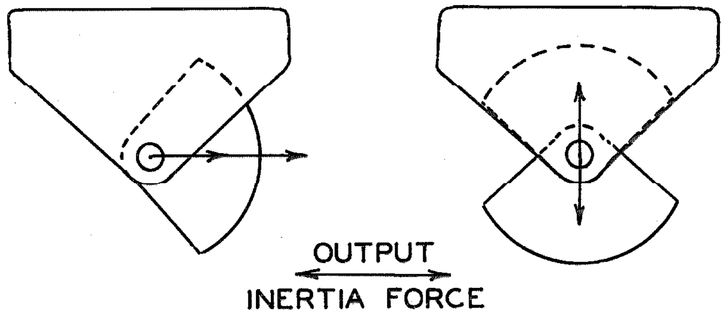
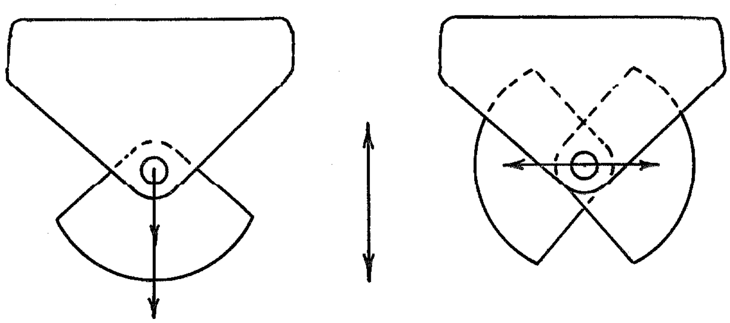


FIG. 3 RESONANCE CURVES OBTAINED FROM TWO SYNCHRONIZED VIBRATION GENERATORS AT DRY CANYON DAM

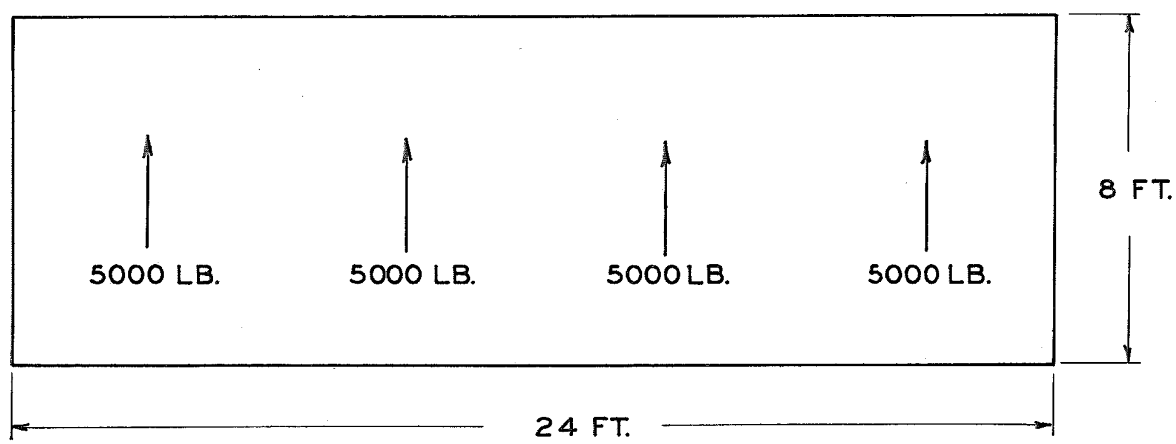


a. PREFERRED DIRECTION OF OUTPUT FORCE
(STRONGER DIRECTION)

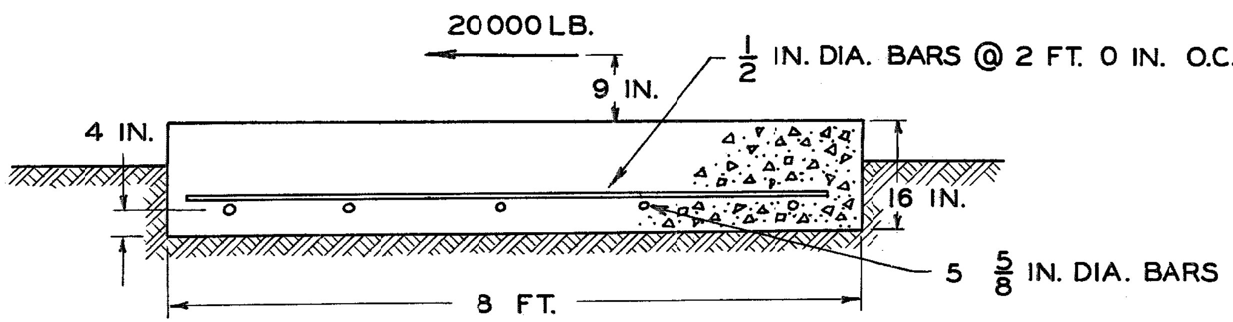


b. WEAKER DIRECTION OF OUTPUT FORCE
(PERMISSIBLE FOR LOW & INTERMEDIATE FORCES)

FIG. 4 PREFERRED ORIENTATION OF VIBRATION GENERATOR OUTPUT INERTIA FORCE



PLAN



SECTION OF 16 IN. THICK SLAB

FIG. 5 CONCRETE FOUNDATION FOR MOUNTING FOUR IN PHASE SYNCHRONIZED VIBRATION GENERATORS

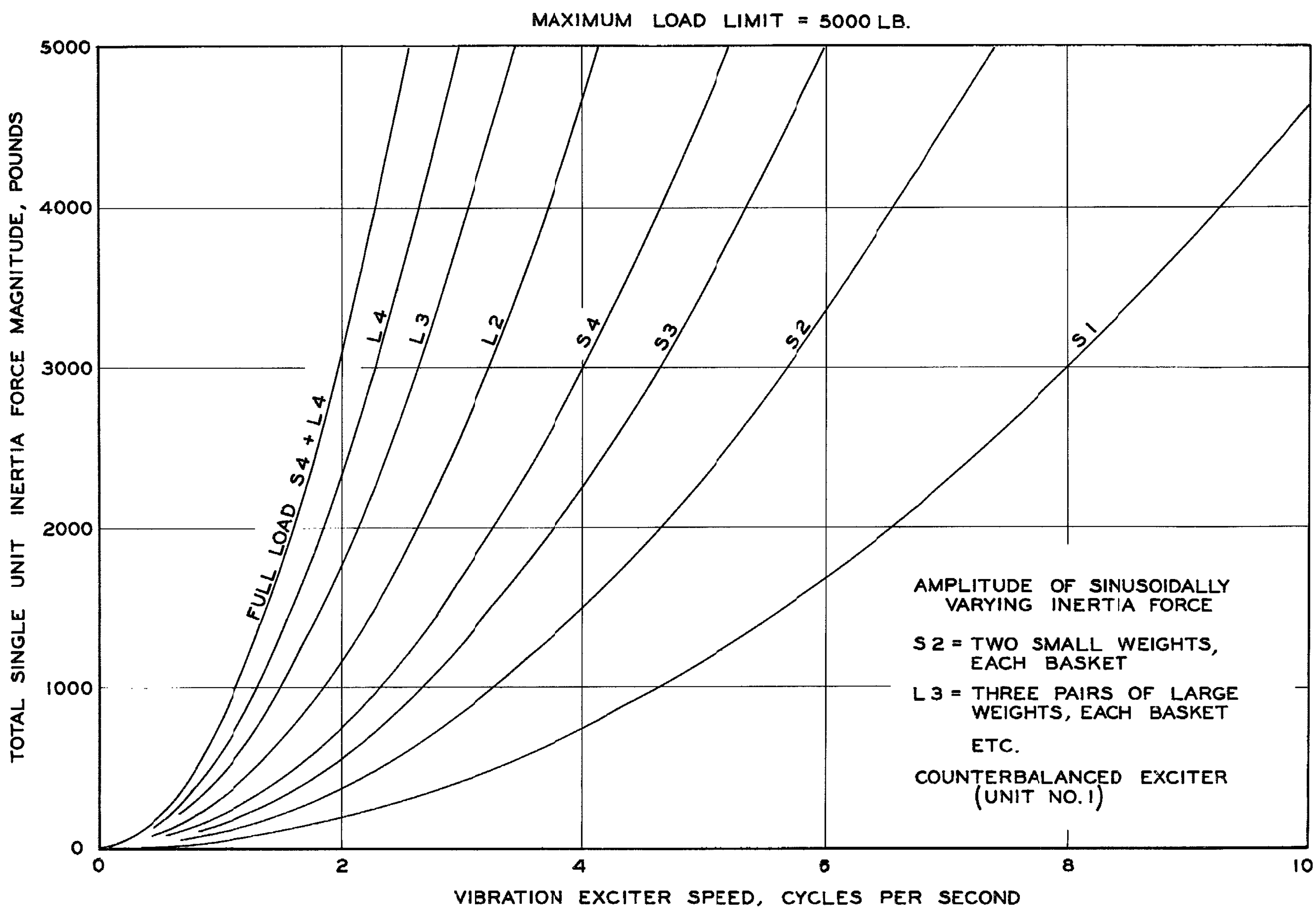


FIG. 6 VIBRATION GENERATOR FORCE OUTPUT VS. SPEED - COUNTERBALANCED

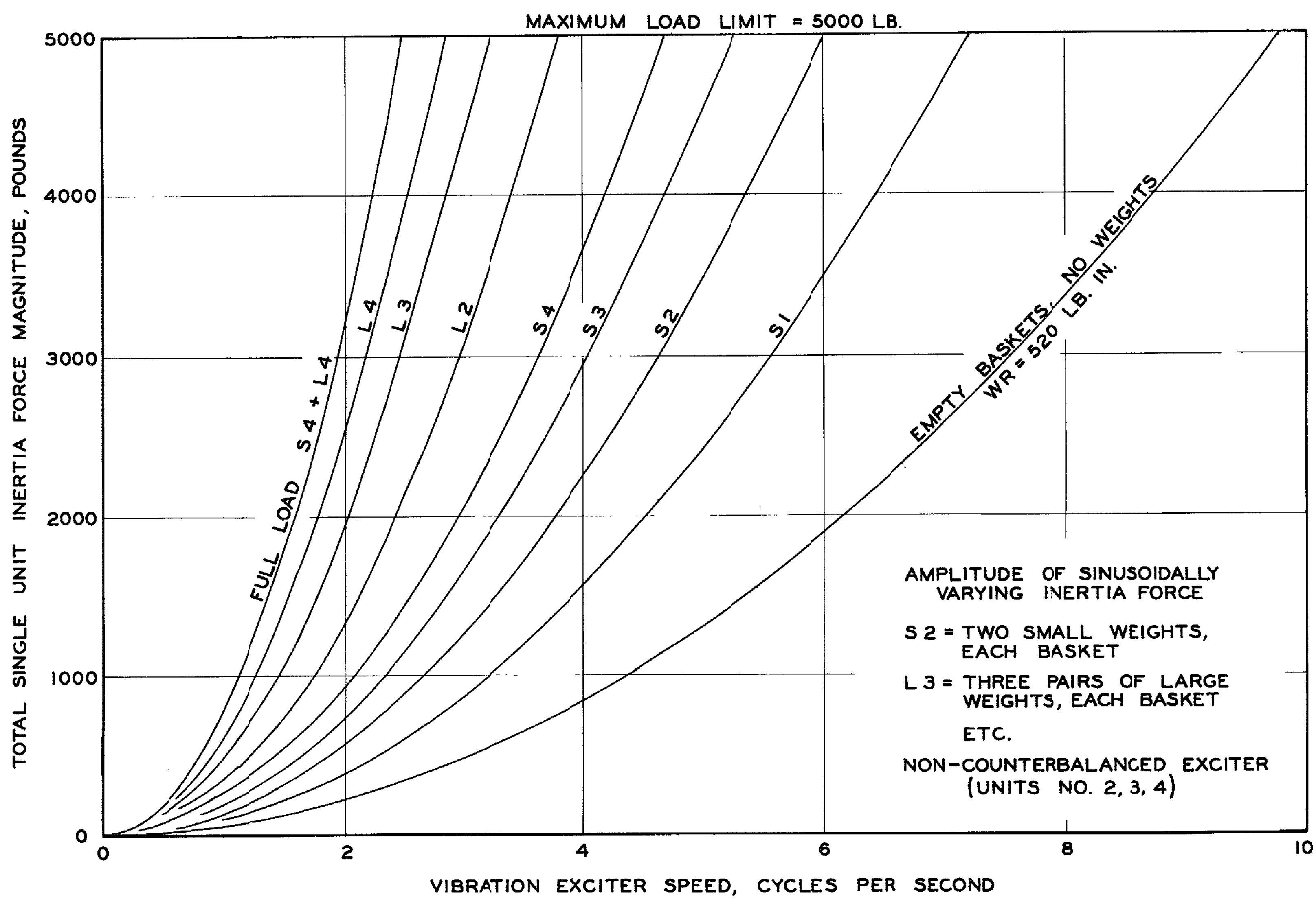
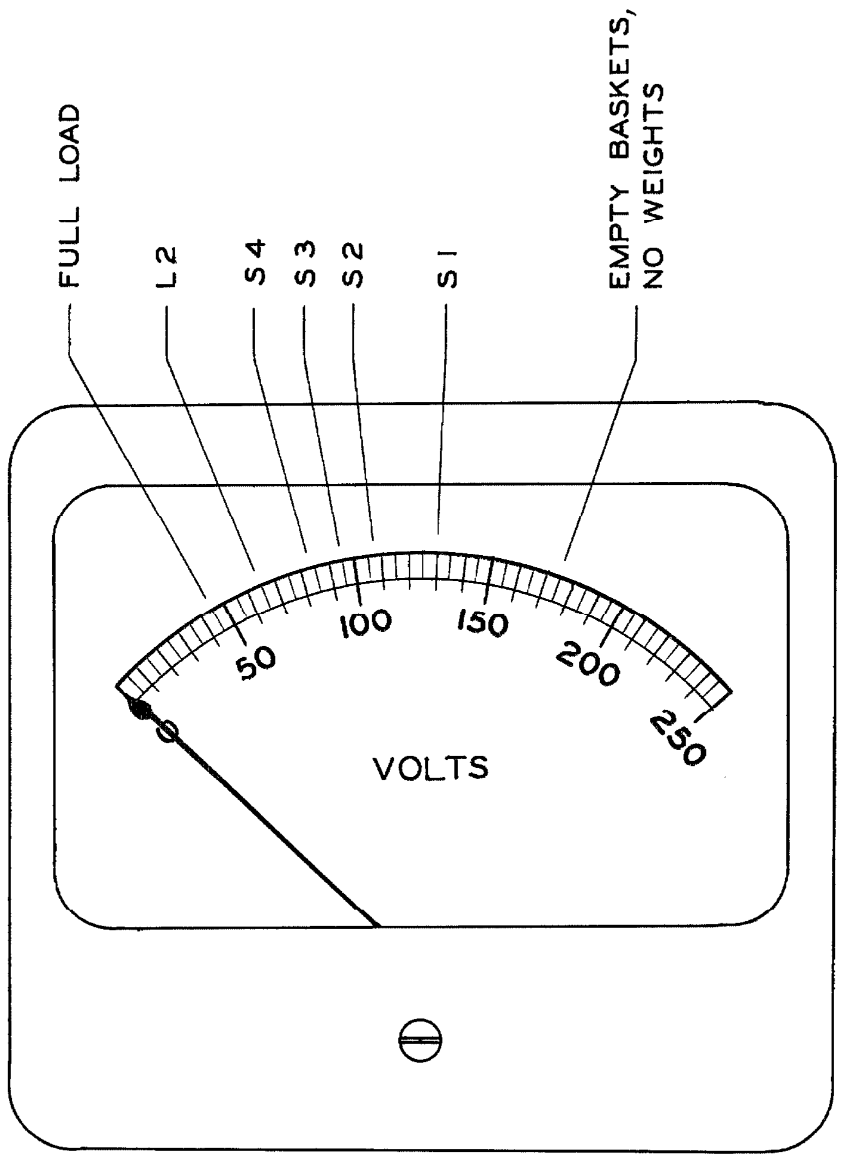


FIG. 7 VIBRATION GENERATOR FORCE OUTPUT VS. SPEED - NON-COUNTERBALANCED



EXCITER SPEED

NON-COUNTERBALANCED VIBRATION GENERATOR
STANDARD 3 TO 1 TRANSMISSION
1 CYCLE PER SECOND = 18 VOLTS

FIG. 8 VIBRATION GENERATOR SPEED LIMITS FOR TYPICAL LEAD WEIGHT LOADS.

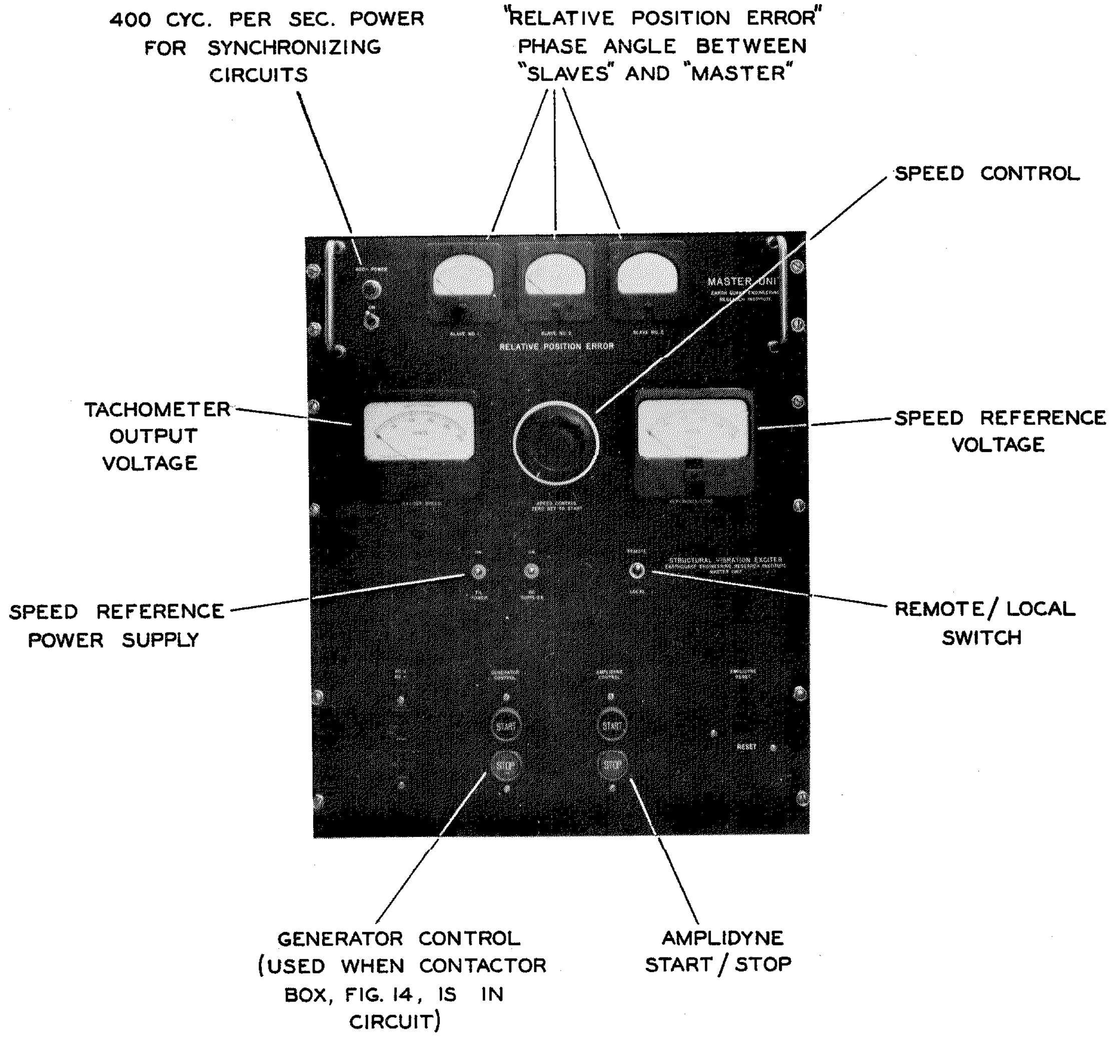


FIG. 9 FRONT PANEL OF "MASTER" CONTROL UNIT SHOWING MAJOR CONTROLS

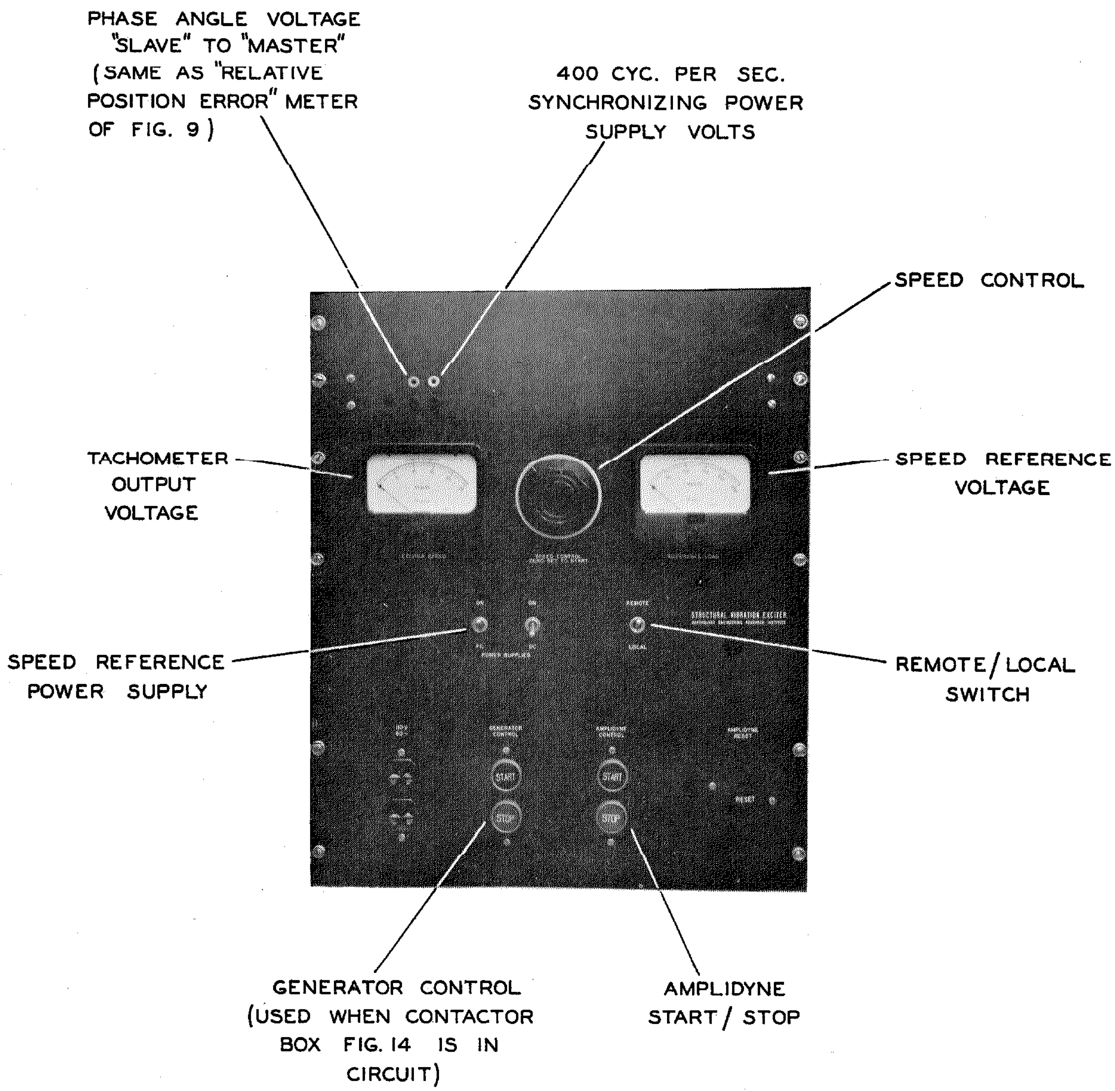


FIG. 10 FRONT PANEL OF "SLAVE" CONTROL UNIT SHOWING MAJOR CONTROLS

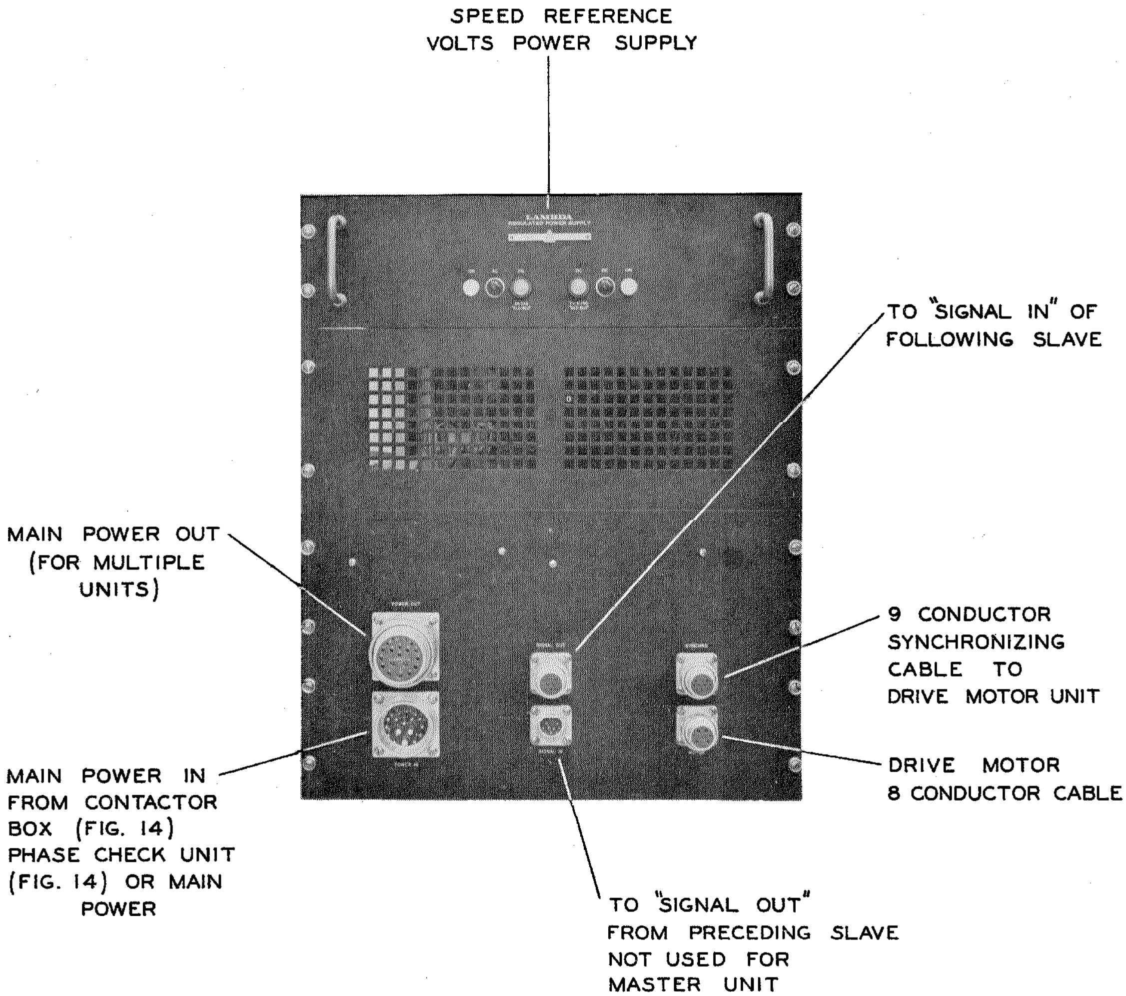


FIG. 11 CABLE CONNECTION PANEL OF CONTROL UNITS

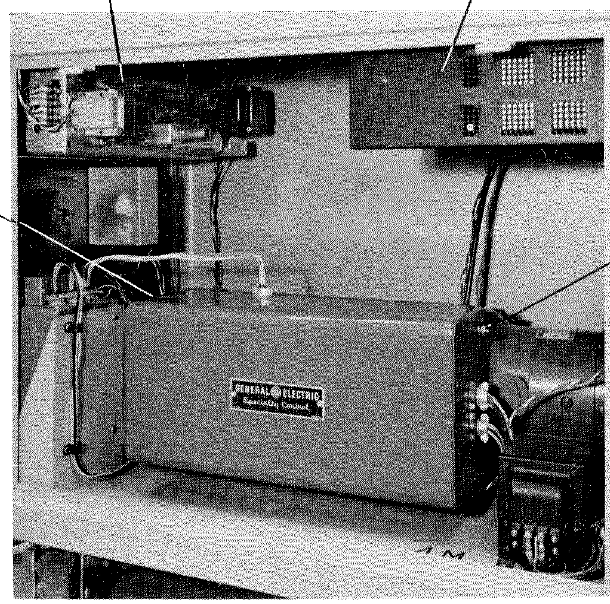


FIG. 12 AMPLIDYNE AND CONTROL AMPLIFIER - MASTER UNIT

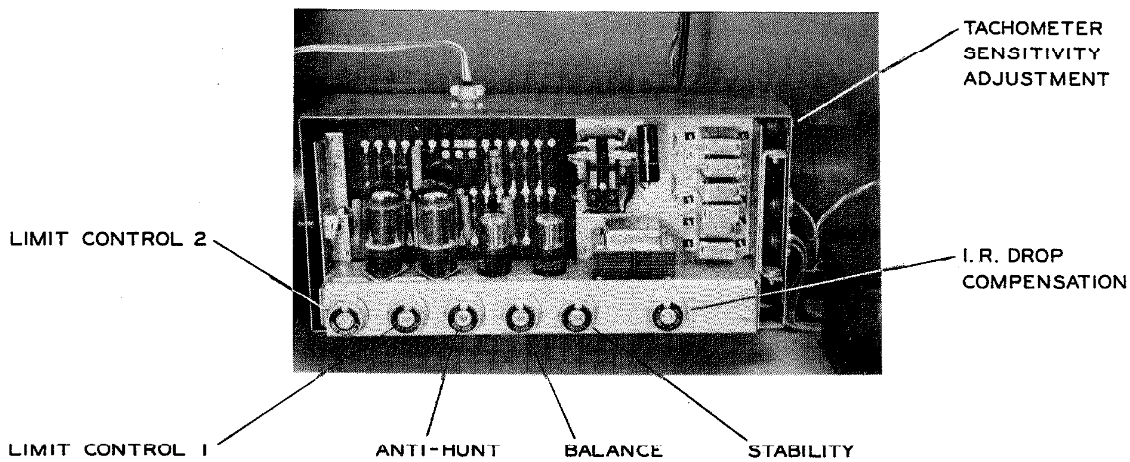


FIG. 13 AMPLIDYNE ELECTRONIC AMPLIFIER CONTROLS

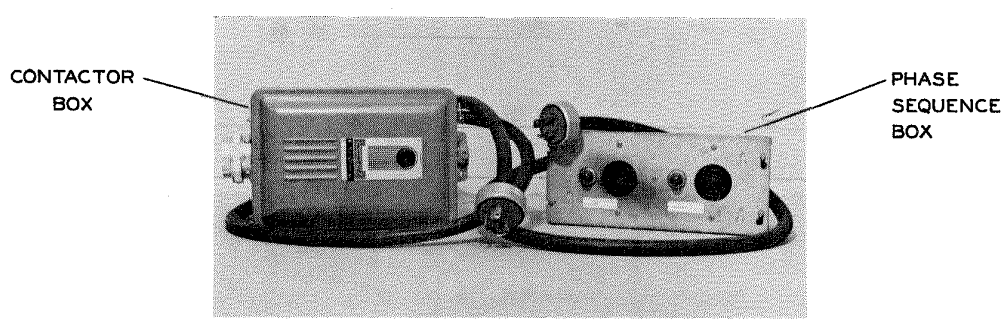


FIG. 14 CONTACTOR BOX AND PHASE SEQUENCE BOX FOR MAIN POWER INPUT

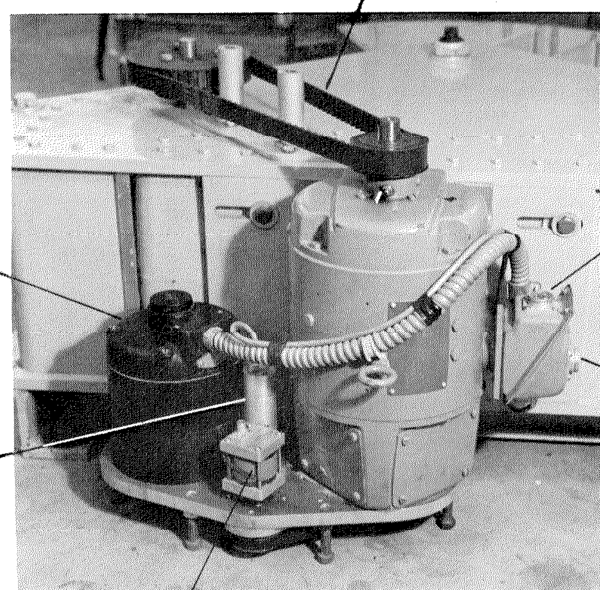


FIG. 15 DRIVE MOTOR AND CONTROL ASSEMBLY

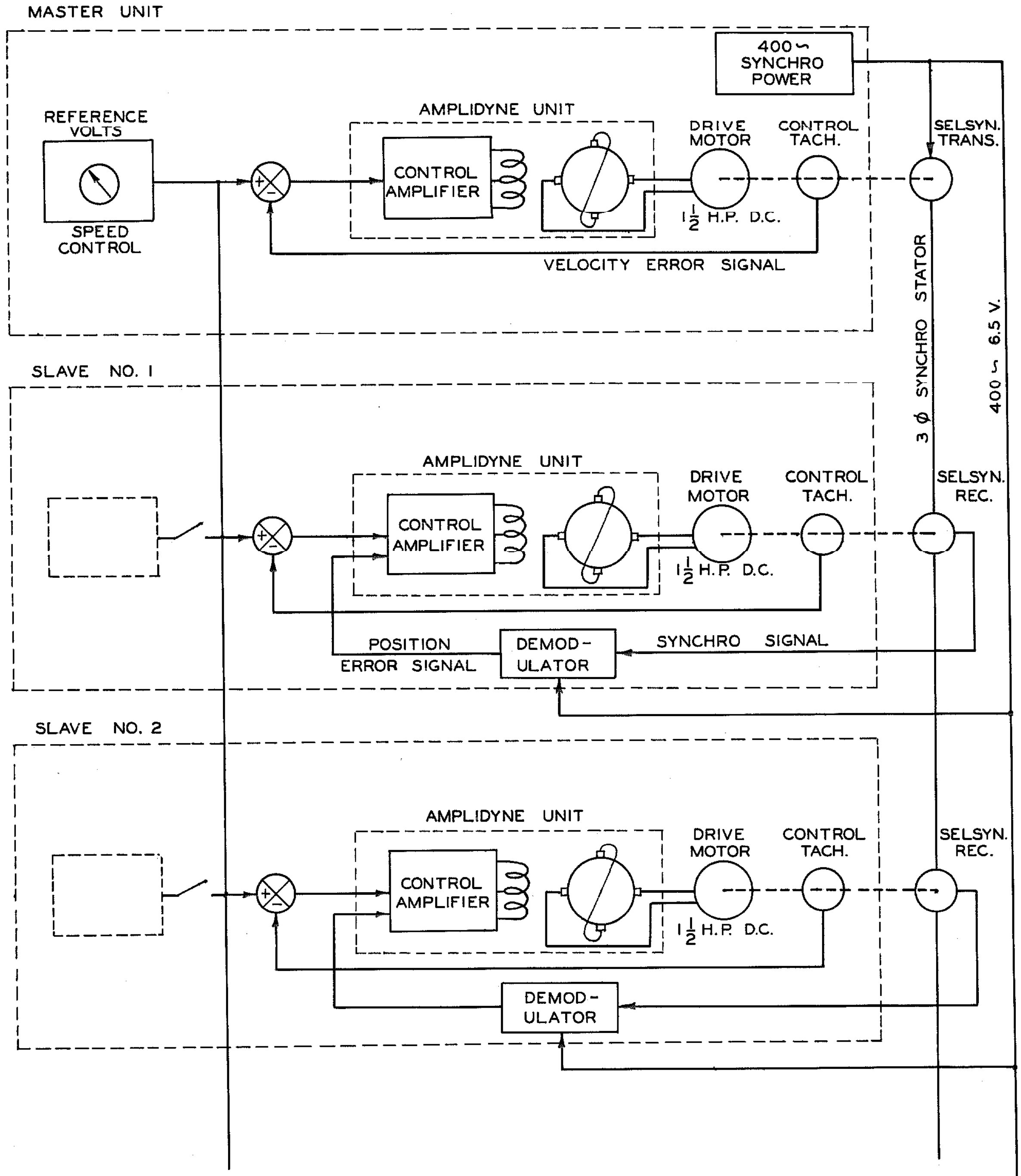
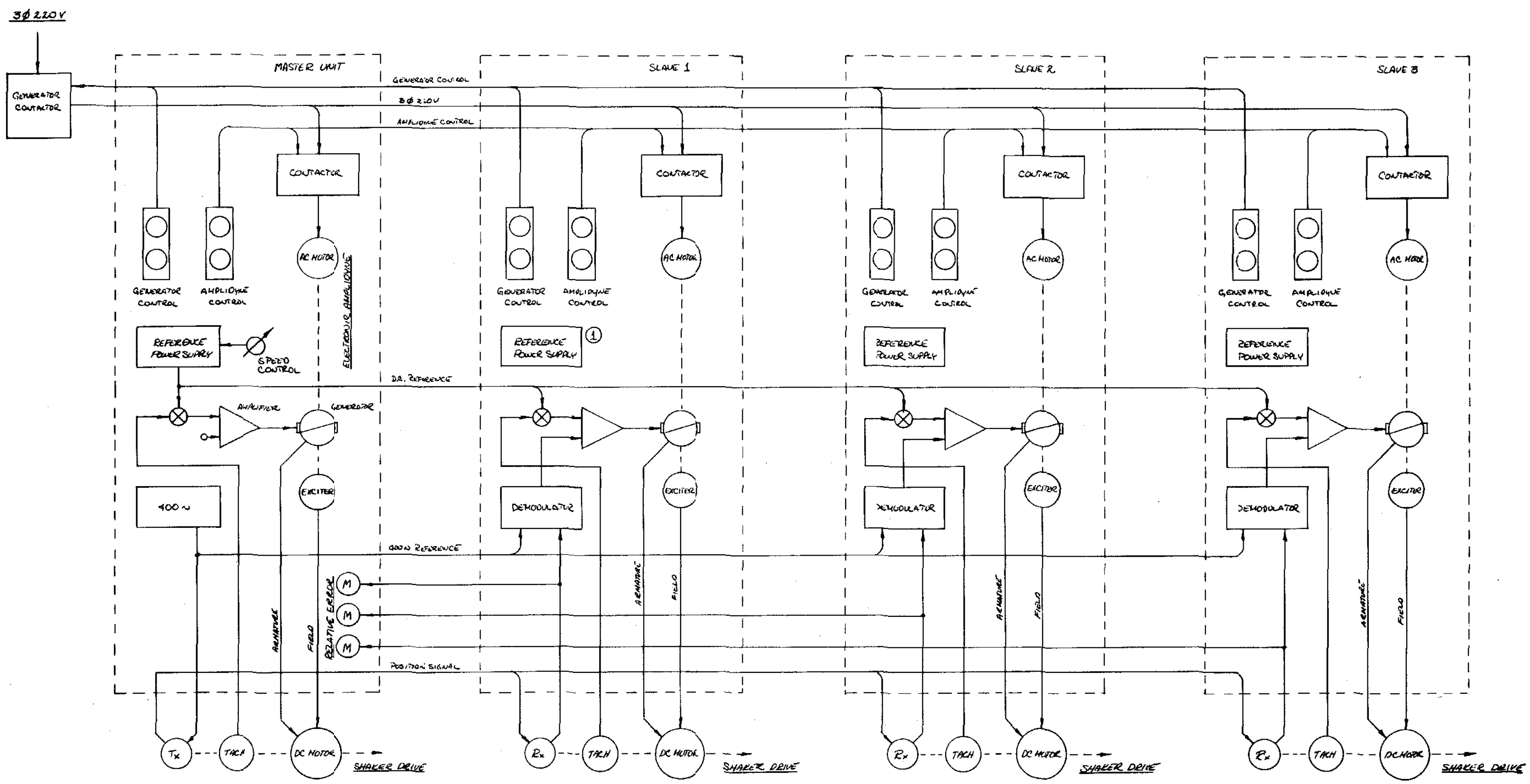
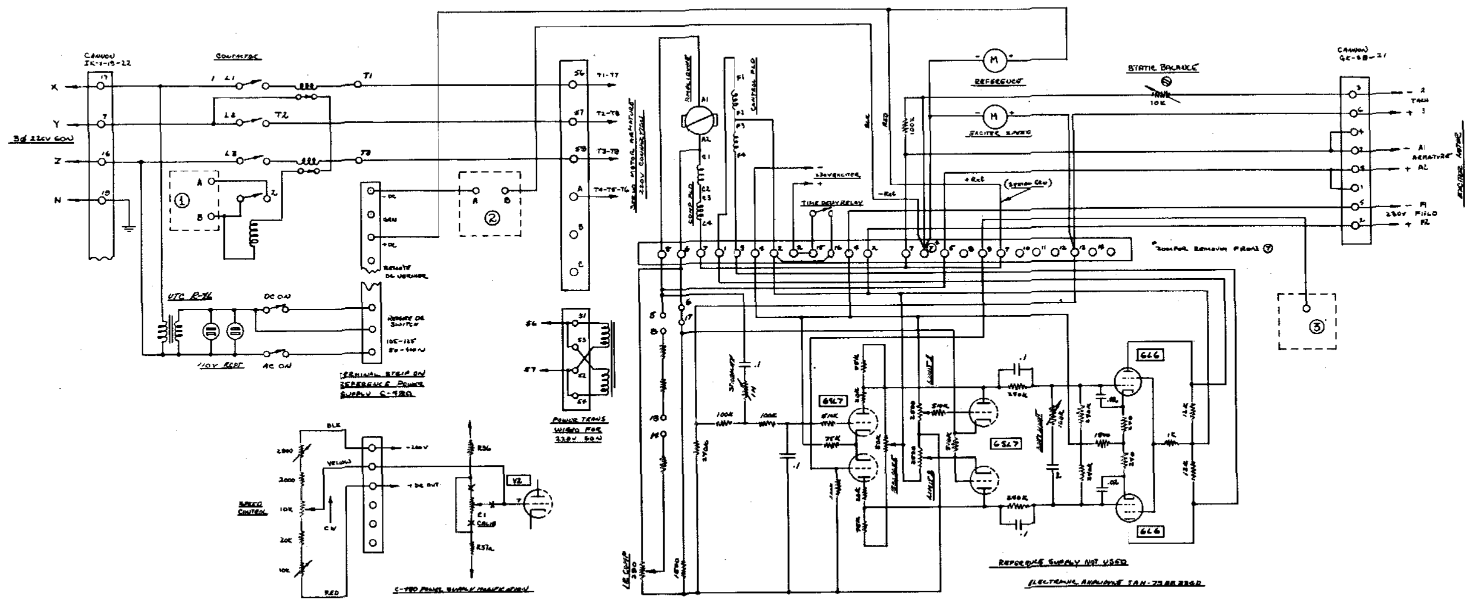


FIG. 16 SCHEMATIC DIAGRAM OF SYNCHRONIZED MULTI-UNIT VIBRATION GENERATOR SYSTEM



NOTES
① SLAVE REFERENCE POWER SUPPLIES USED FOR LOCAL AND SINGLE SHAKER OPERATION ONLY

Fig. 17 Block Diagram of Synchronized Vibration Generator System.



NOTES

1. SEE CONTACTOR CONTROL DRAWING FOR PILOT WIRING
2. SEE REFERENCE CONTROL DRAWING FOR REMOTE-LOCAL SWITCH WIRING
3. SEE SYNCHRO CONTROL DRAWING FOR DEMODULATOR WIRING

Fig. 18 Electronically Controlled Amplidyne Drive for Synchronized Vibration Generators.

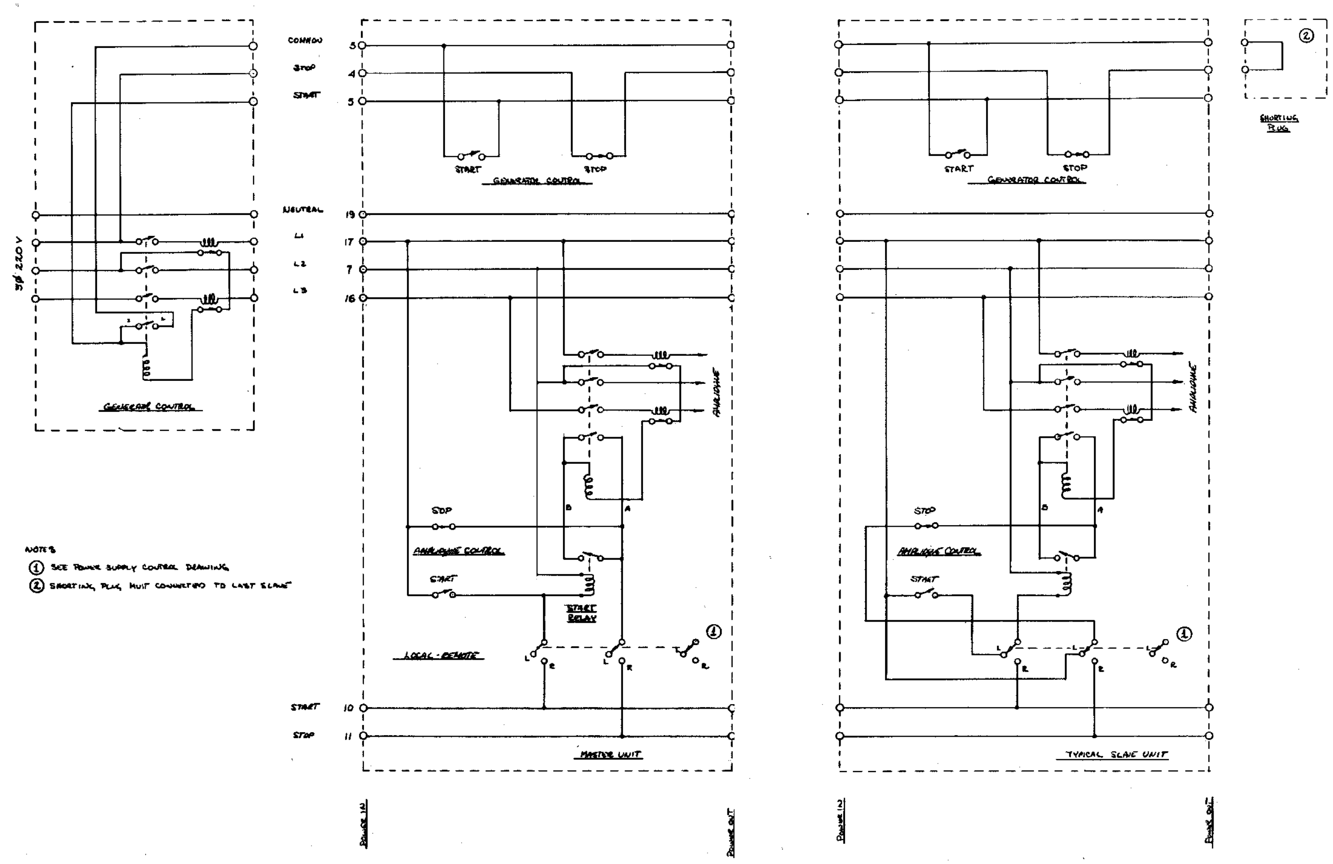
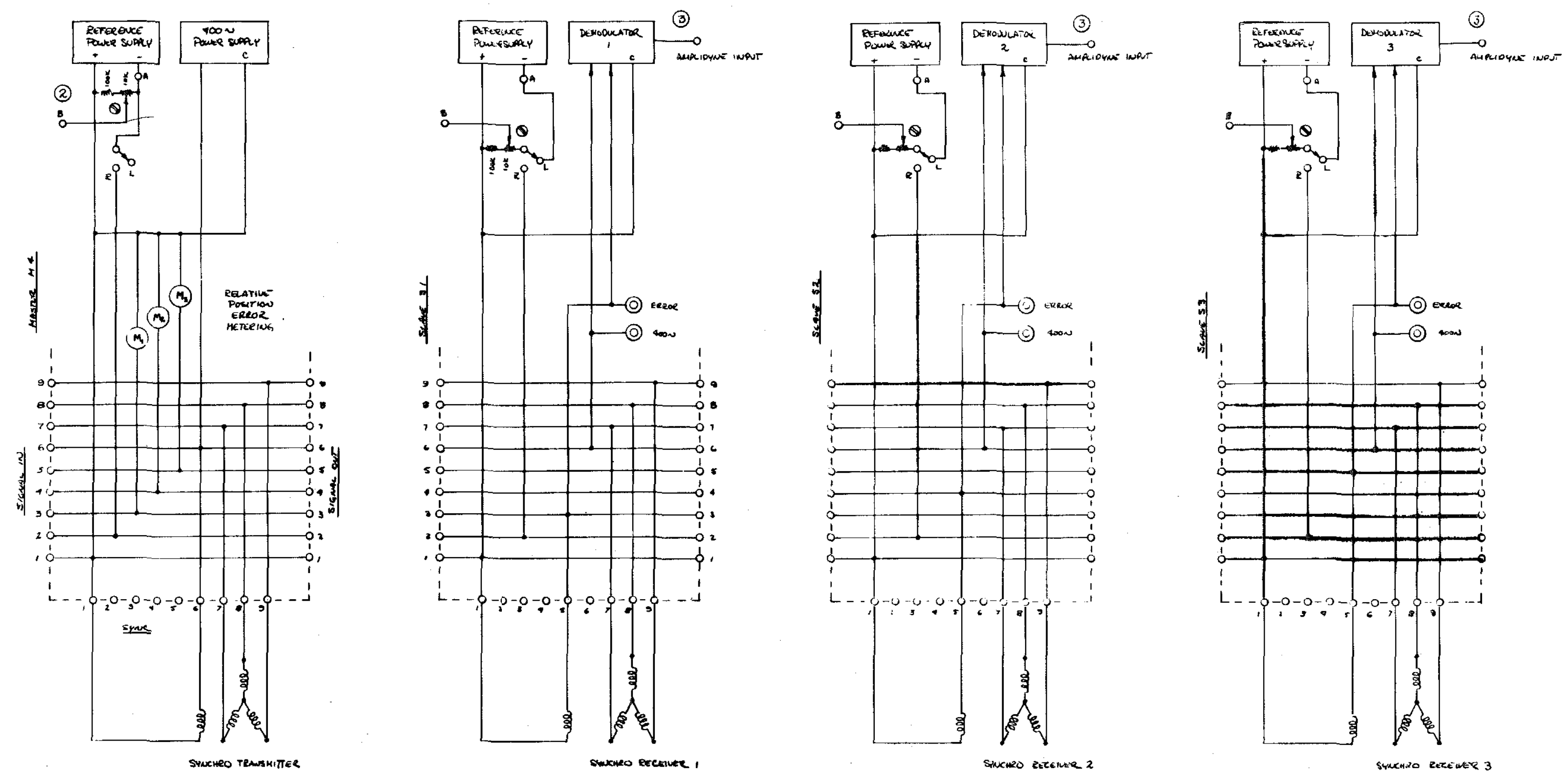


Fig. 19 Three Phase Power Control for Synchronized Vibration Generator Drive.



NOTES

○ SEE NOTES ON ELECTRONIC DRIVE SCHEMATIC DIAGRAM

Fig. 20 Synchronizing Circuits for Vibration Generator Drive.

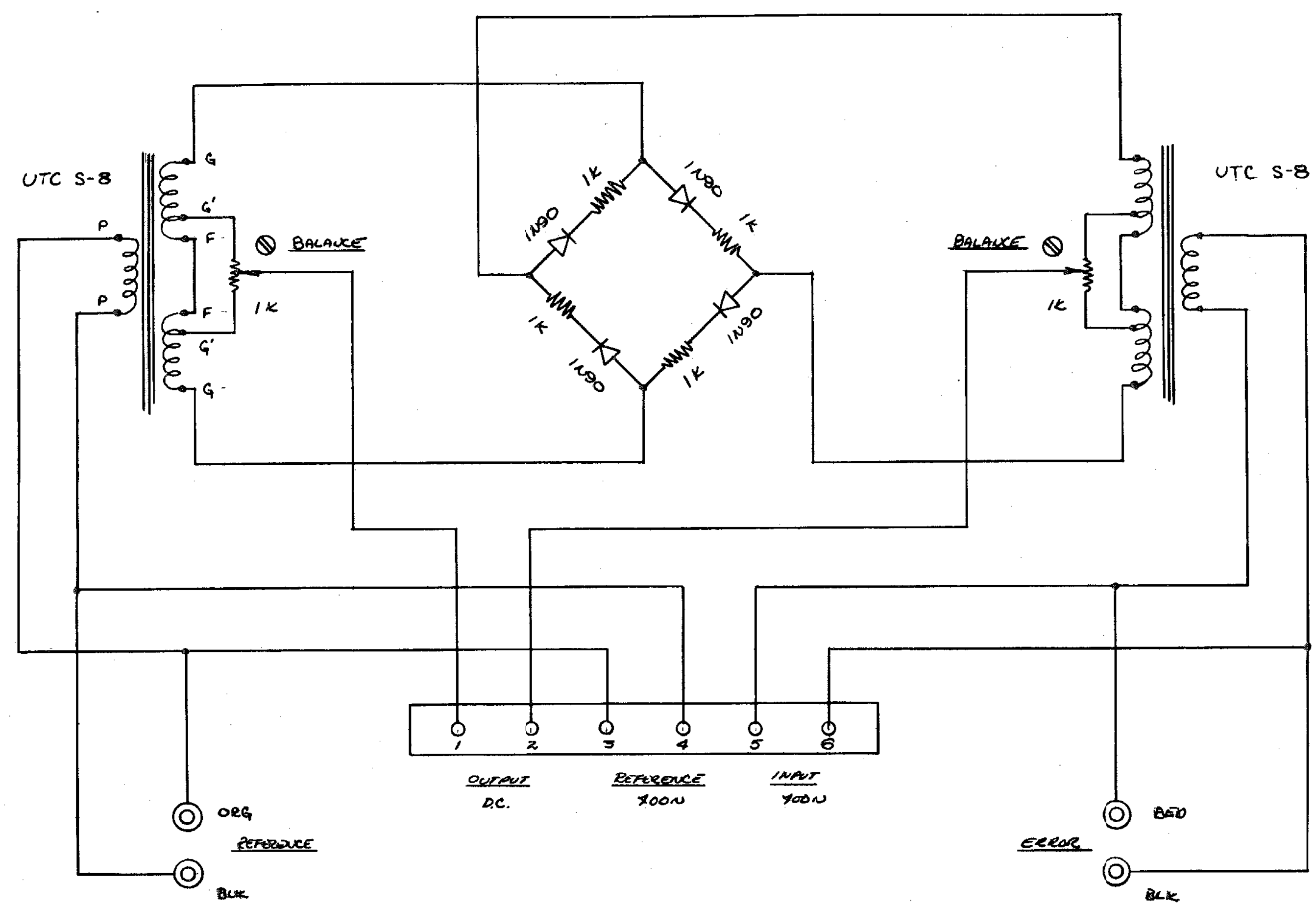


Fig. 21 Circuit Diagram for Synchro System Demodulator.

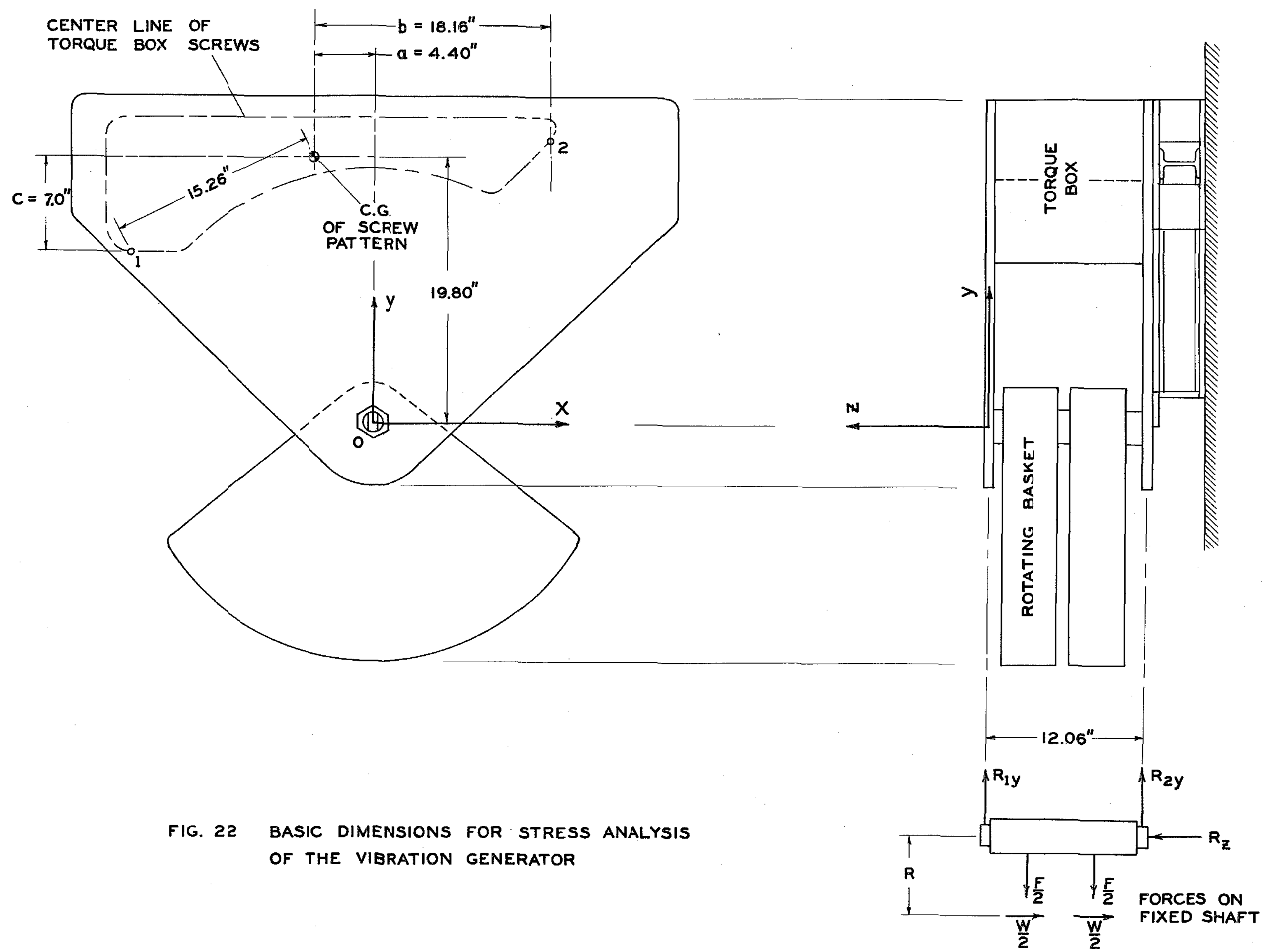
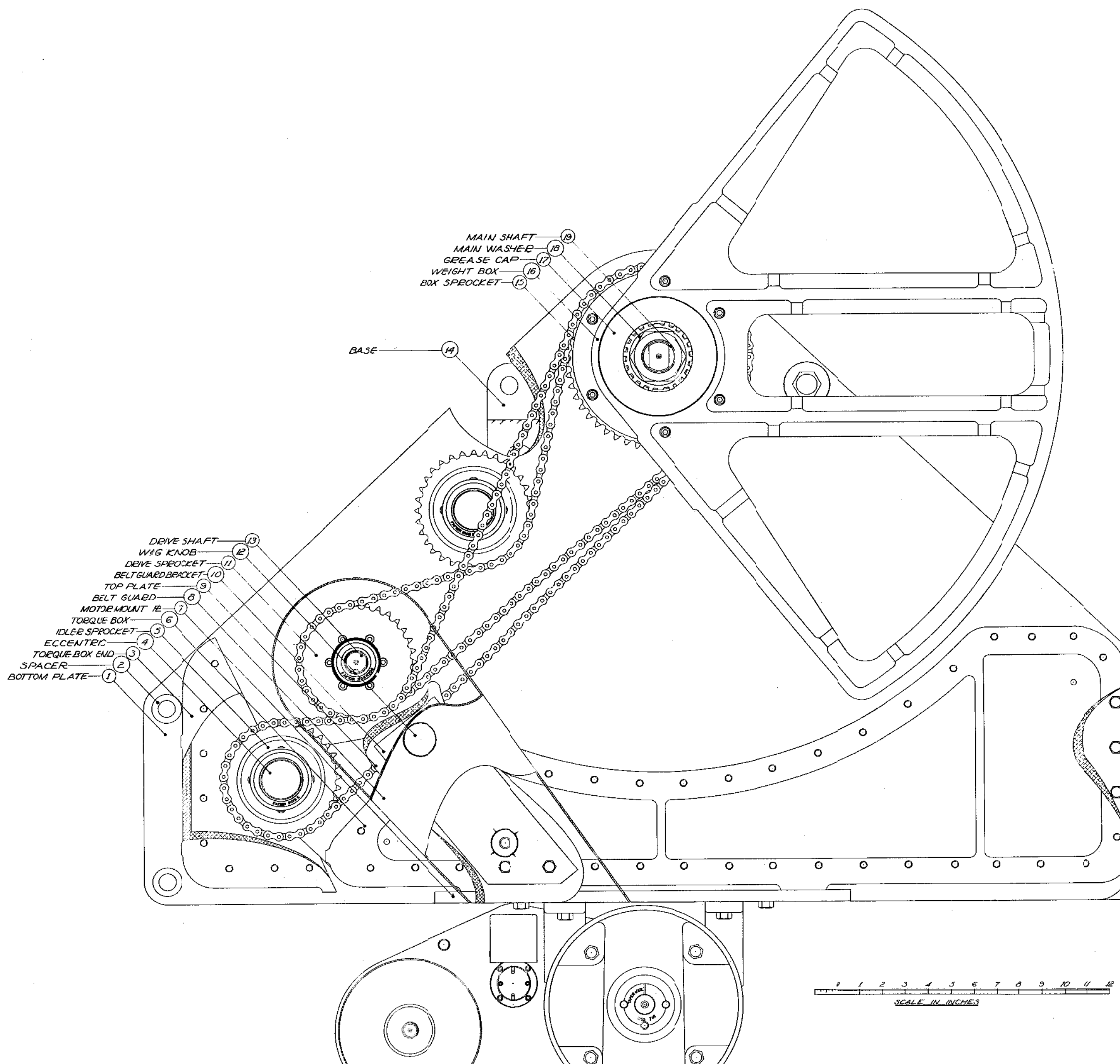
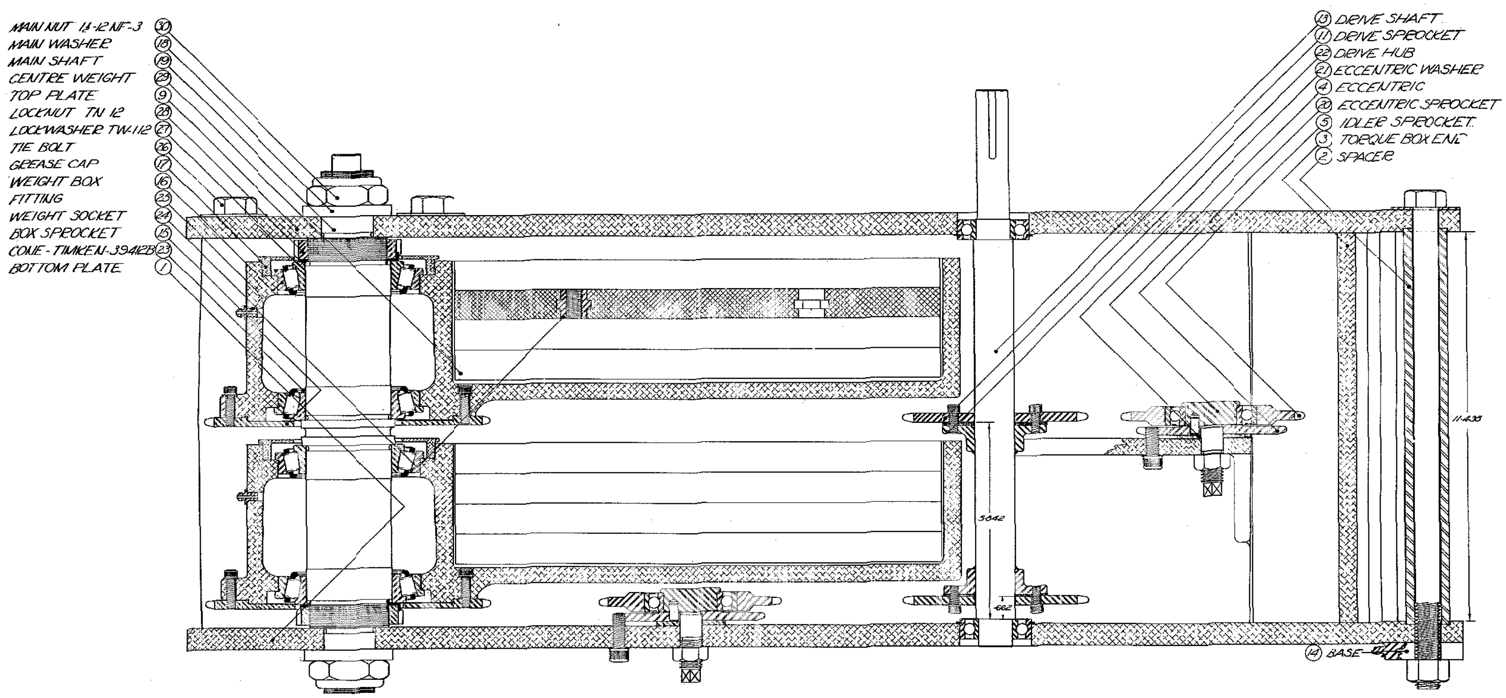
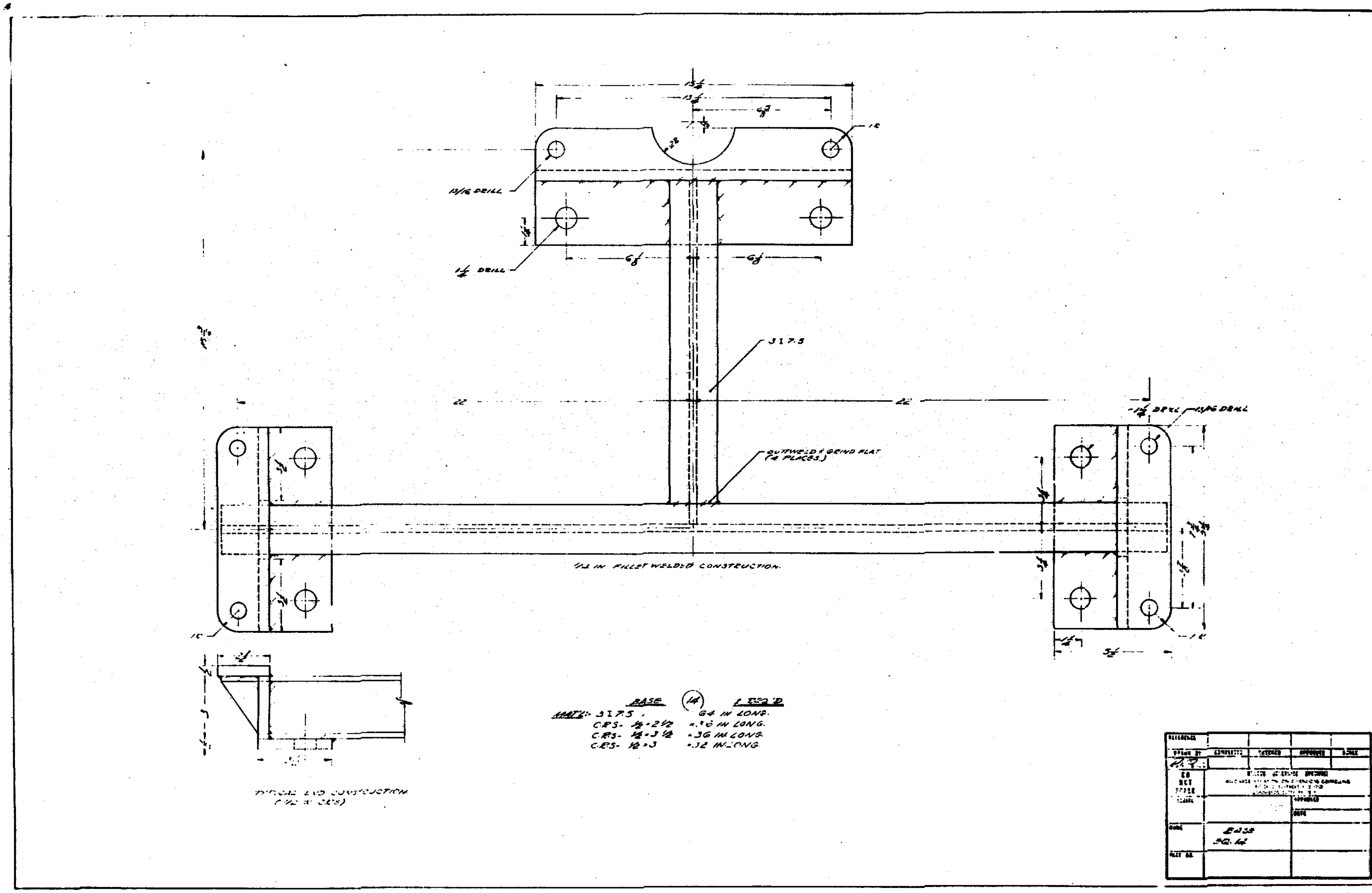


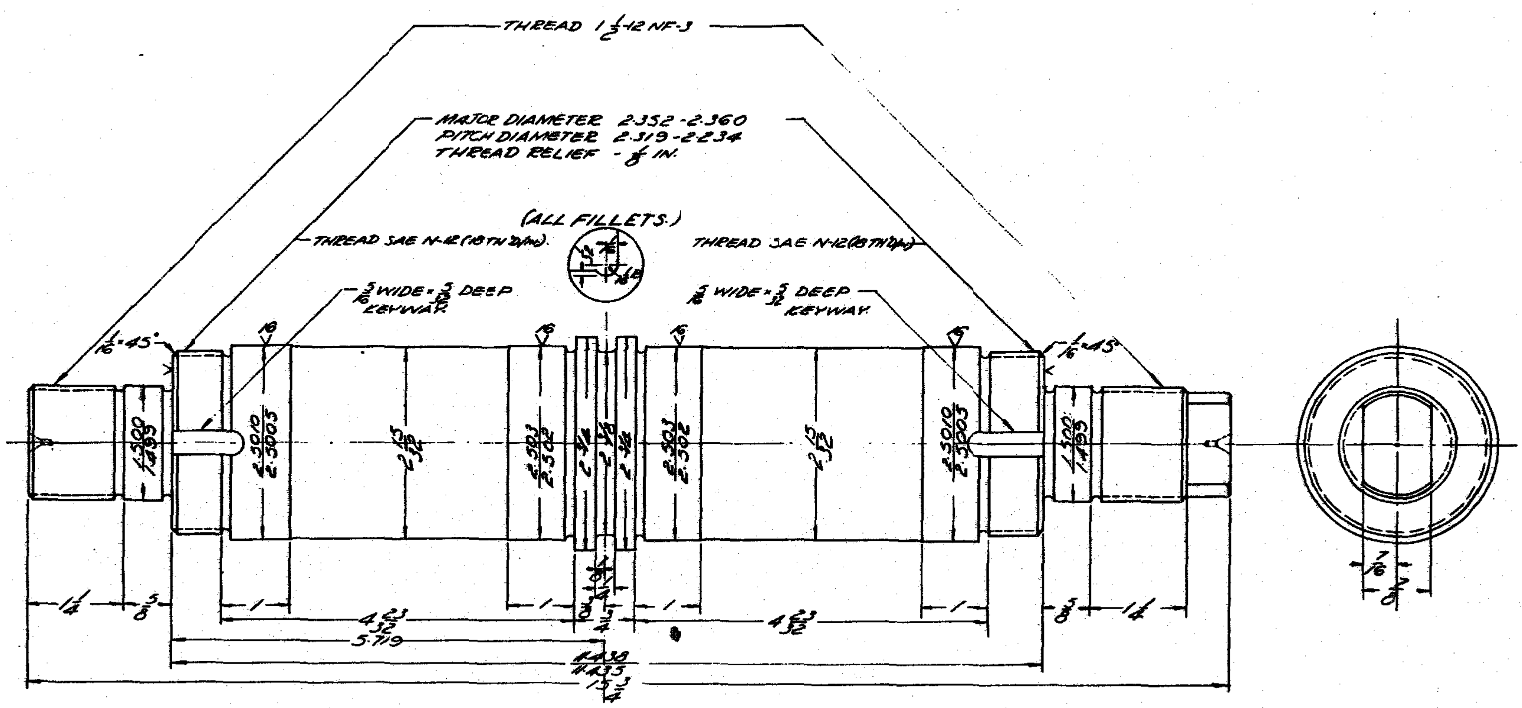
FIG. 22 BASIC DIMENSIONS FOR STRESS ANALYSIS OF THE VIBRATION GENERATOR


MAIN SHAFT 19
MAIN WASHER 18
GREASE CAP 17
WEIGHT BOX 16
BOX SPROCKET 15
BASE 14
DRIVE SHAFT 13
W&G KNOB 12
DRIVE SPROCKET 11
BELT GUARD BRACKET 10
TOP PLATE 9
BELT GUARD 8
MOTOR MOUNT 7
TORQUE BOX 6
IDLER SPROCKET 5
ECCENTRIC 4
TORQUE BOX END 3
SPACER 2
BOTTOM PLATE 1
0 1 2 3 4 5 6 7 8 9 10 11 12
SCALE IN INCHES



MAIN NUT 1¼-12 NF-3 (30)
MAIN WASHER (18)
MAIN SHAFT (19)
CENTRE WEIGHT (29)
TOP PLATE (9)
LOCKNUT TN 12 (28)
LOCKWASHER TW-112 (27)
TIE BOLT (26)
GREASE CAP (17)
WEIGHT BOX (16)
FITTING (25)
WEIGHT SOCKET (24)
BOX SPROCKET (15)
CONE - TIMKEN-39412B (23)
BOTTOM PLATE (1)
(13) DRIVE SHAFT
(11) DRIVE SPROCKET
(22) DRIVE HUB
(21) ECCENTRIC WASHER
(4) ECCENTRIC
(20) ECCENTRIC SPROCKET
(5) IDLER SPROCKET
(3) TORQUE BOX END
(2) SPACER
(14) BASE


13/16 DRILL
1/4 DRILL
317.5
OUTWELD & GRIND FLAT
(4 PLACES)
1/2 IN FILLET WELDED CONSTRUCTION.
TYPICAL END CONSTRUCTION
(1/2 IN CRS)
BASE (14) 1 REQ'D
MAT'L:- 317.5 . 64 IN LONG.
C.R.S- 1/2 x 2 1/2 x 36 IN LONG.
C.R.S- 1/2 x 3 1/2 x 36 IN LONG.
C.R.S- 1/2 x 3 x 32 IN LONG.
REFERENCE
DRAWN BY
COMPUTED
CHECKED
APPROVED
SCALE
DO NOT SCALE
APPROVED
DATE
NAME
BASE
SQ. 14
PART NO.



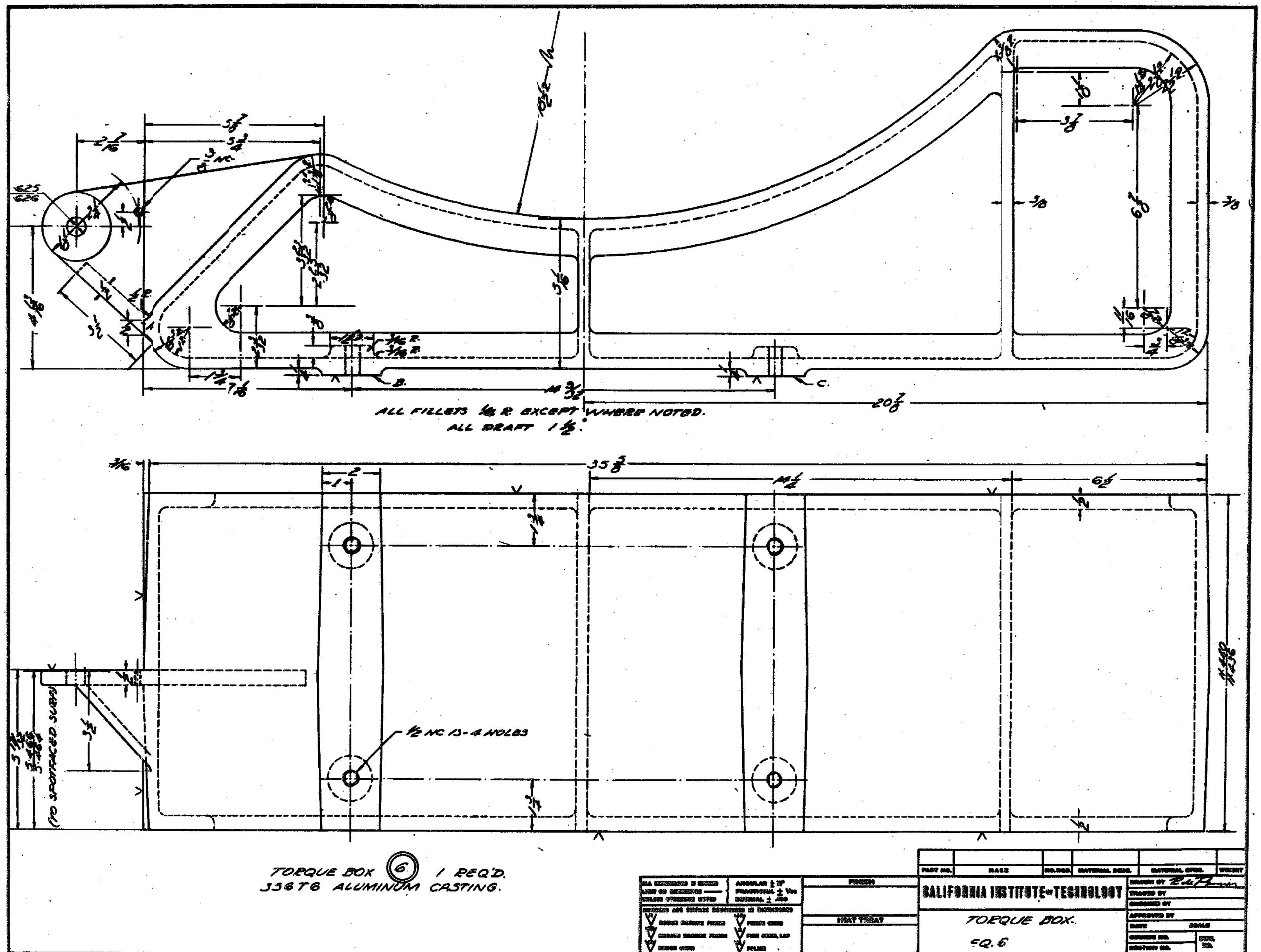
MAIN SHAFT (19) 1 REQ'D.

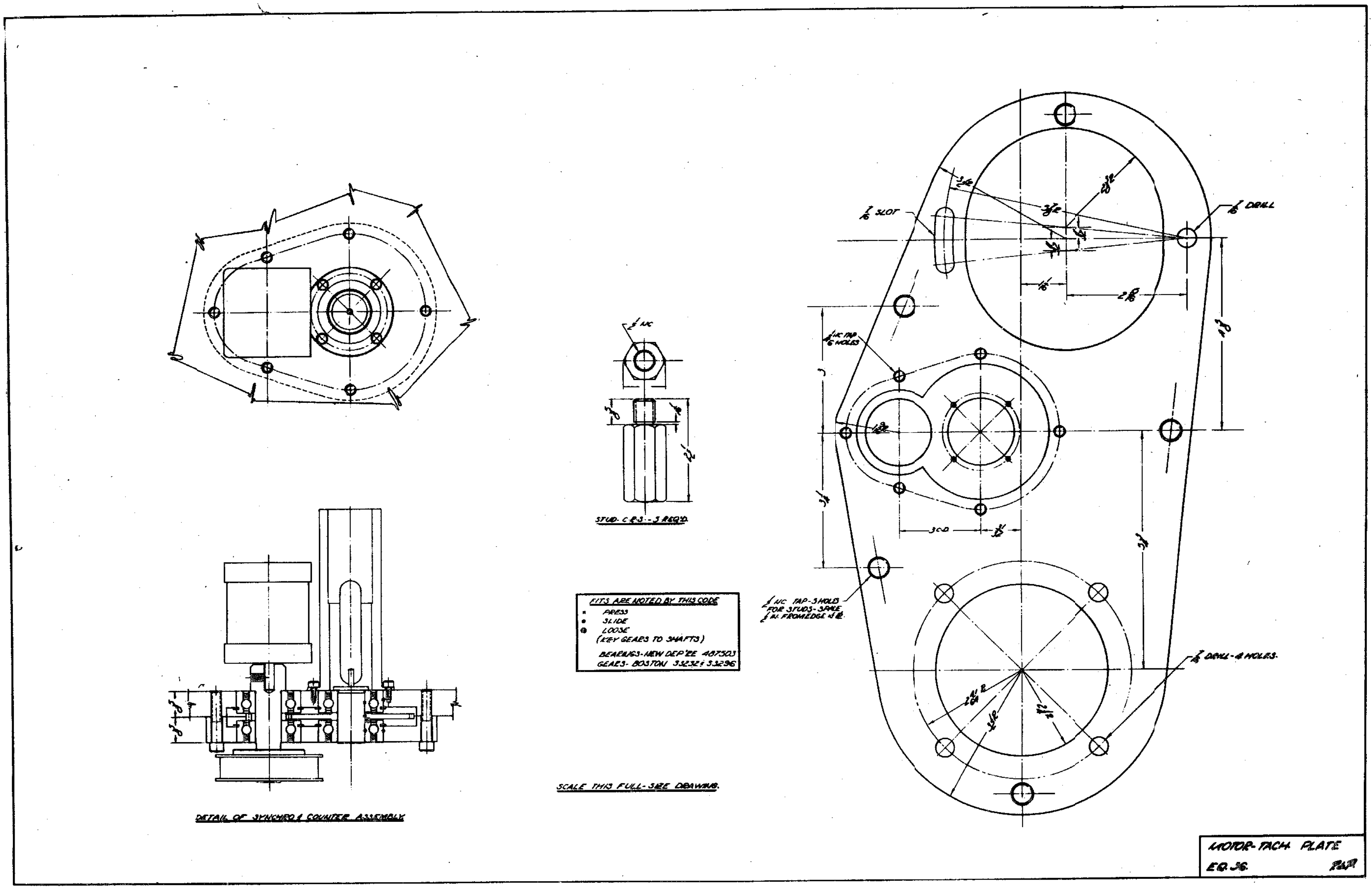
4130 STEEL- 2 3/4 DIAM × 16 in LONG
NORMALIZE
QUENCH FROM 1575°F. IN WATER.
TEMPER TO 490°F.

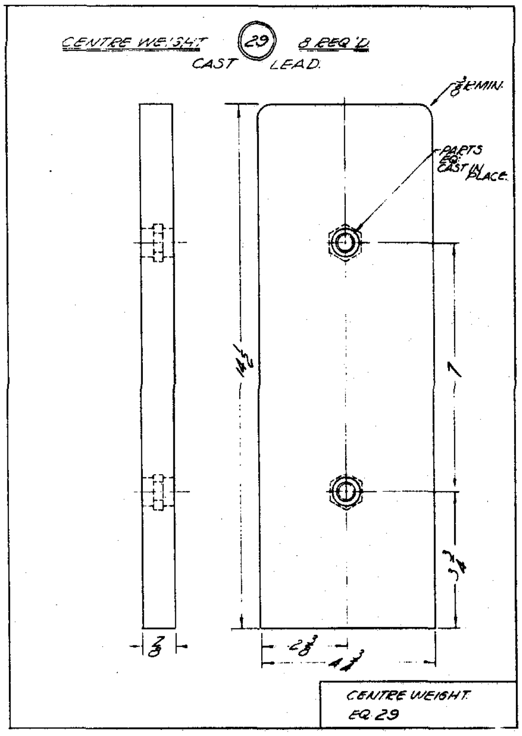
PART NO.	NAME	NO. REQD.	MATERIAL DESG.	MATERIAL SPEC.	WEIGHT
CALIFORNIA INSTITUTE of TECHNOLOGY				DRAWN BY R. de Pinner	
				TRACED BY	
				CHECKED BY	
MAIN SHAFT				APPROVED BY	
				DATE	SCALE
EQ 19				COURSE NO.	DWG. NO.
				SECTION NO.	

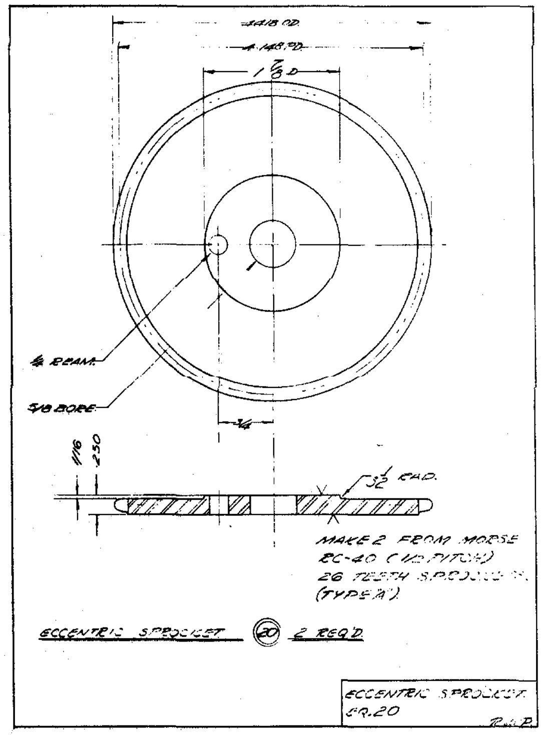
FINISH

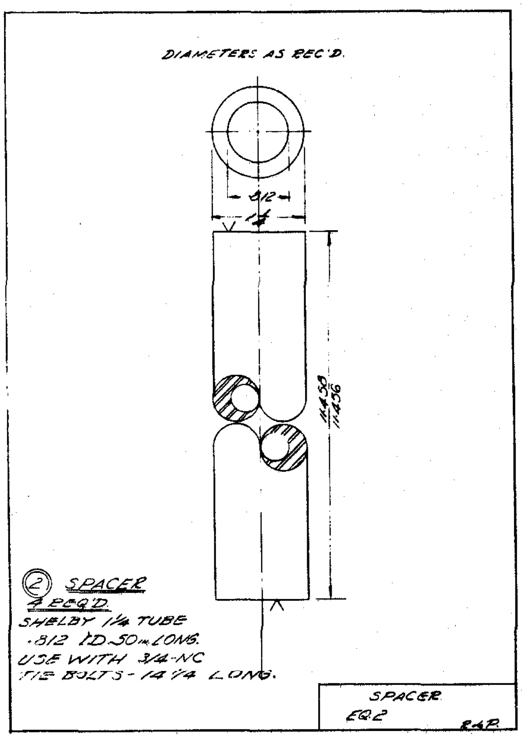
HEAT TREAT

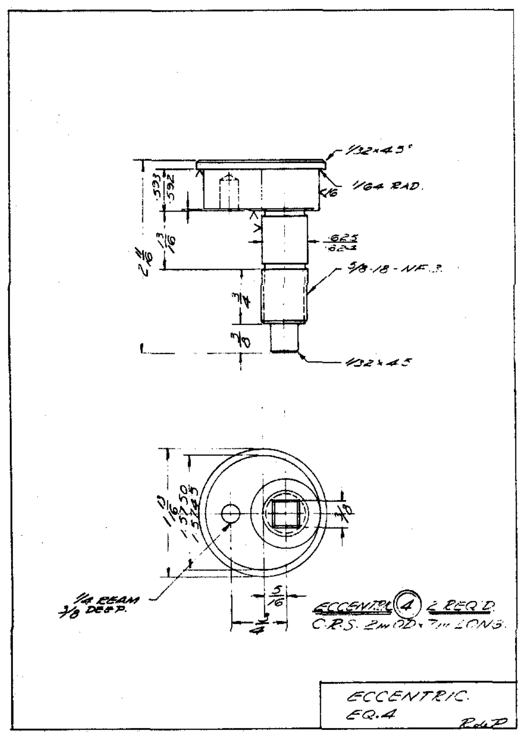

ALL FILLETS 1/8 R. EXCEPT WHERE NOTED.
ALL DRAFT 1 1/2°
1/2 NC 13 - 4 HOLES
(TO SPOTFACED SURF.)
TORQUE BOX 6 1 REQ'D.
356 T6 ALUMINUM CASTING.
FINISH
HEAT TREAT
CALIFORNIA INSTITUTE of TECHNOLOGY
TORQUE BOX.
FQ. 6

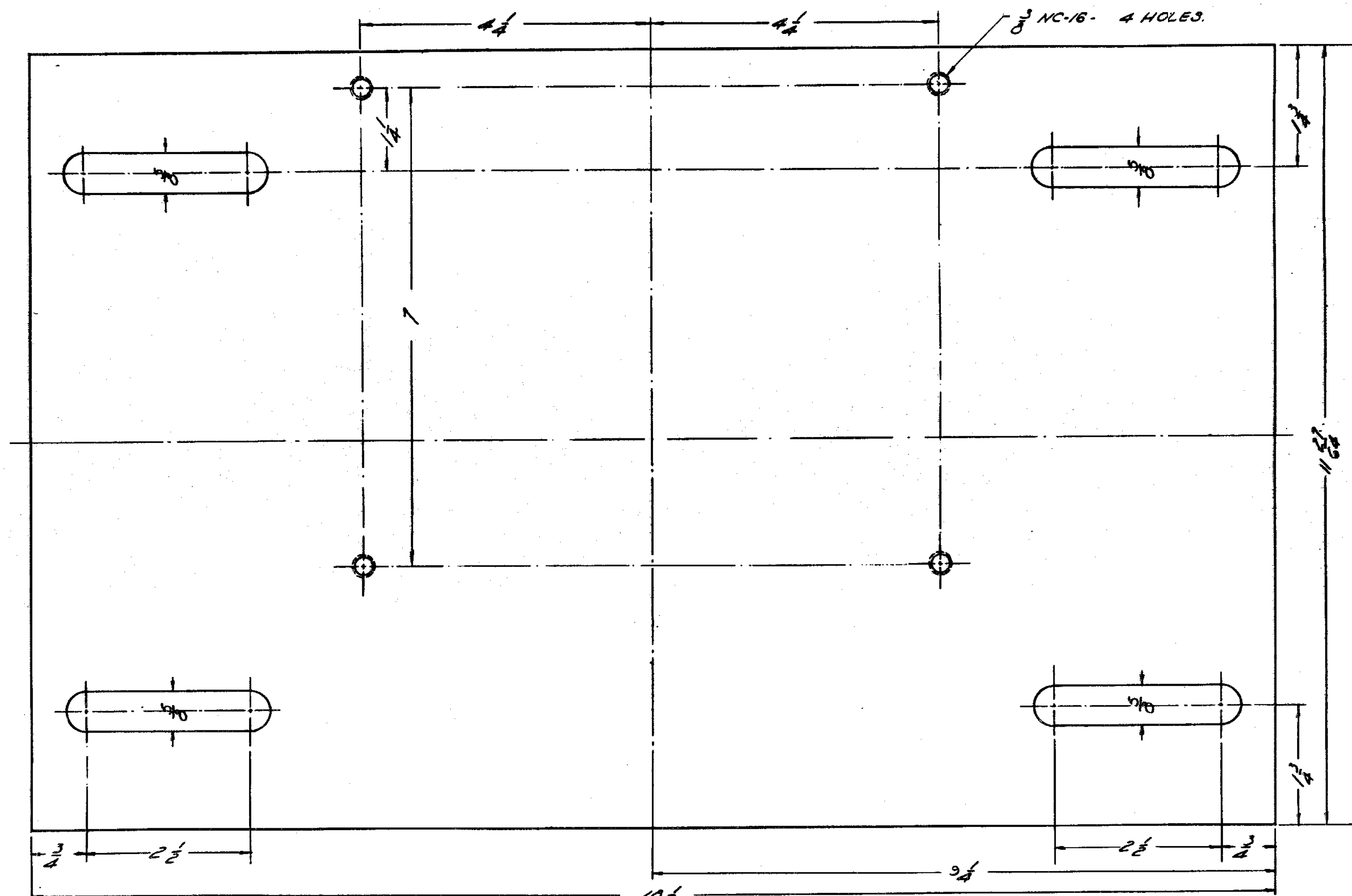

STUD - C.R.S. - 3 REQ'D.
FITS ARE NOTED BY THIS CODE
PRESS
SLIDE
LOOSE
(KEY GEARS TO SHAFTS)
BEARINGS - NEW DEP'RE 487503
GEARS - BOSTON 33232 & 33296
SCALE THIS FULL-SIZE DRAWING.
DETAIL OF SYNCHRO & COUNTER ASSEMBLY
DRILL
SLOT
DRILL - 4 HOLES.
NC TAP - 3 HOLES FOR STUDS - SPACE IN. FROM EDGE
NC TAP 6 HOLES
MOTOR-TACH PLATE
EQ. 36.


CENTRE WEIGHT 29 8 REQ'D
CAST LEAD.
PARTS EQ. CAST IN PLACE.
7
CENTRE WEIGHT
EQ.29


$1\frac{7}{8}$ D
1/4 REAM.
5/8 BORE.
3/4
MAKE 2 FROM MORSE
RC-40 (1/2 PITCH)
26 TEETH SPROCKETS.
ECCENTRIC SPROCKET 20 2 REQ'D
ECCENTRIC SPROCKET
EQ.20


DIAMETERS AS REQ'D.
.812
2 SPACER
4 REQ'D.
SHELBY 1¼ TUBE
.812 I.D.-.50 in. LONG.
USE WITH 3/4-NC
TIE BOLTS - 14 ¼ LONG.
SPACER
EQ.2
R.A.P.


1/64 RAD.
5/8-18-NF-3.
1/32 x 45
1/4 REAM 3/8 DEEP.
ECCENTRIC 4 2 REQ'D
C.R.S. 2 in OD x 7 in LONG.
ECCENTRIC
EQ.4



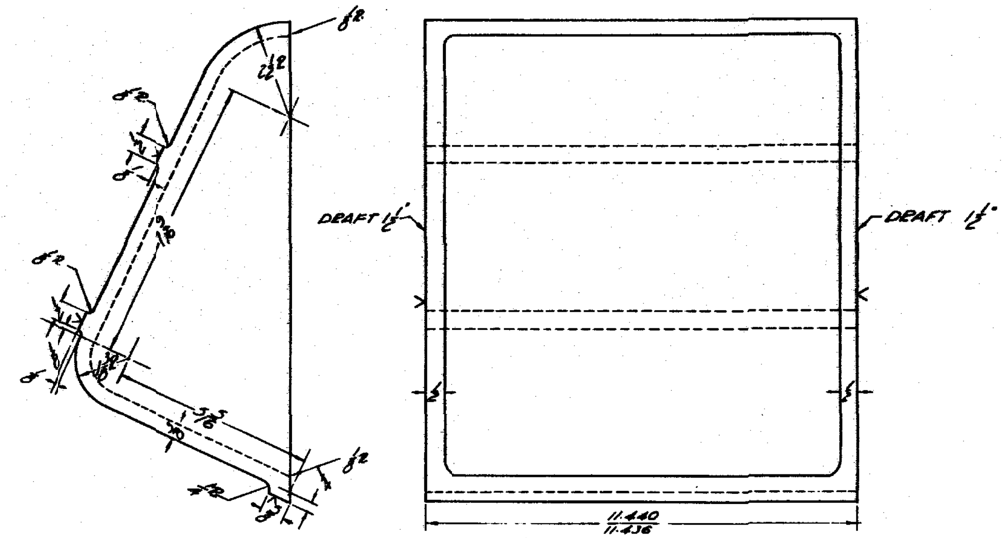
MOTOR MOUNTING PLATE
ALUMINUM $\frac{1}{2} \times 11\frac{1}{2} \times 18\frac{1}{2}$ (7) 1 REQ'D.

PART NO.	NAME	NO. REQ.	MATERIAL DESC.	MATERIAL SPEC.	WEIGHT
CALIFORNIA INSTITUTE OF TECHNOLOGY				DRAWN BY R. [illegible]	
MOTOR MOUNTING PLATE.				TRACED BY	
EQ. 7				CHECKED BY	
				APPROVED BY	
				DATE	SCALE
				COURSE NO.	DWG. NO.
				SECTION NO.	

ALL DIMENSIONS IN INCHES
LIMIT ON DIMENSIONS —
UNLESS OTHERWISE NOTED
ANGULAR $\pm \frac{1}{2}°$
FRACTIONAL $\pm \frac{1}{64}$
DECIMAL $\pm .010$
FINISHES ARE SURFACE ROUGHNESS IN MICROINCHES
ROUGH MACHINE FINISH — FINISH GRIND
SMOOTH MACHINE FINISH — FINE GRIND, LAP
ROUGH GRIND — POLISH

FINISH

HEAT TREAT



TORQUE BOX END. (3) 1 REQ'D.
356 T6 ALUMINUM CASTING.

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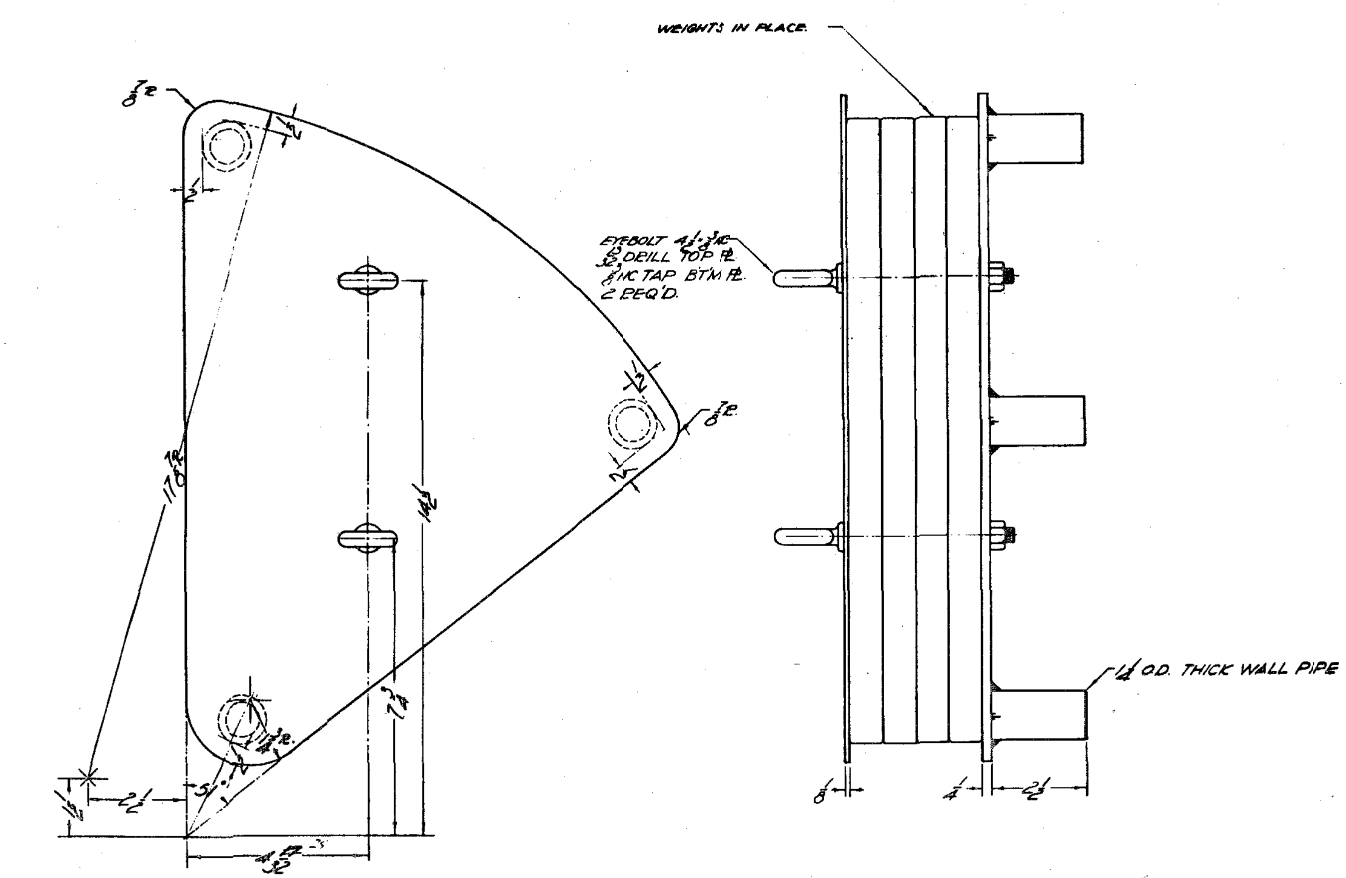
TORQUE BOX END

EQ. 3

HEAT TREAT



SIDE WEIGHT RACK (31) 4 REQ'D - 2 L.H. & 2 R.H.
MILD STEEL.

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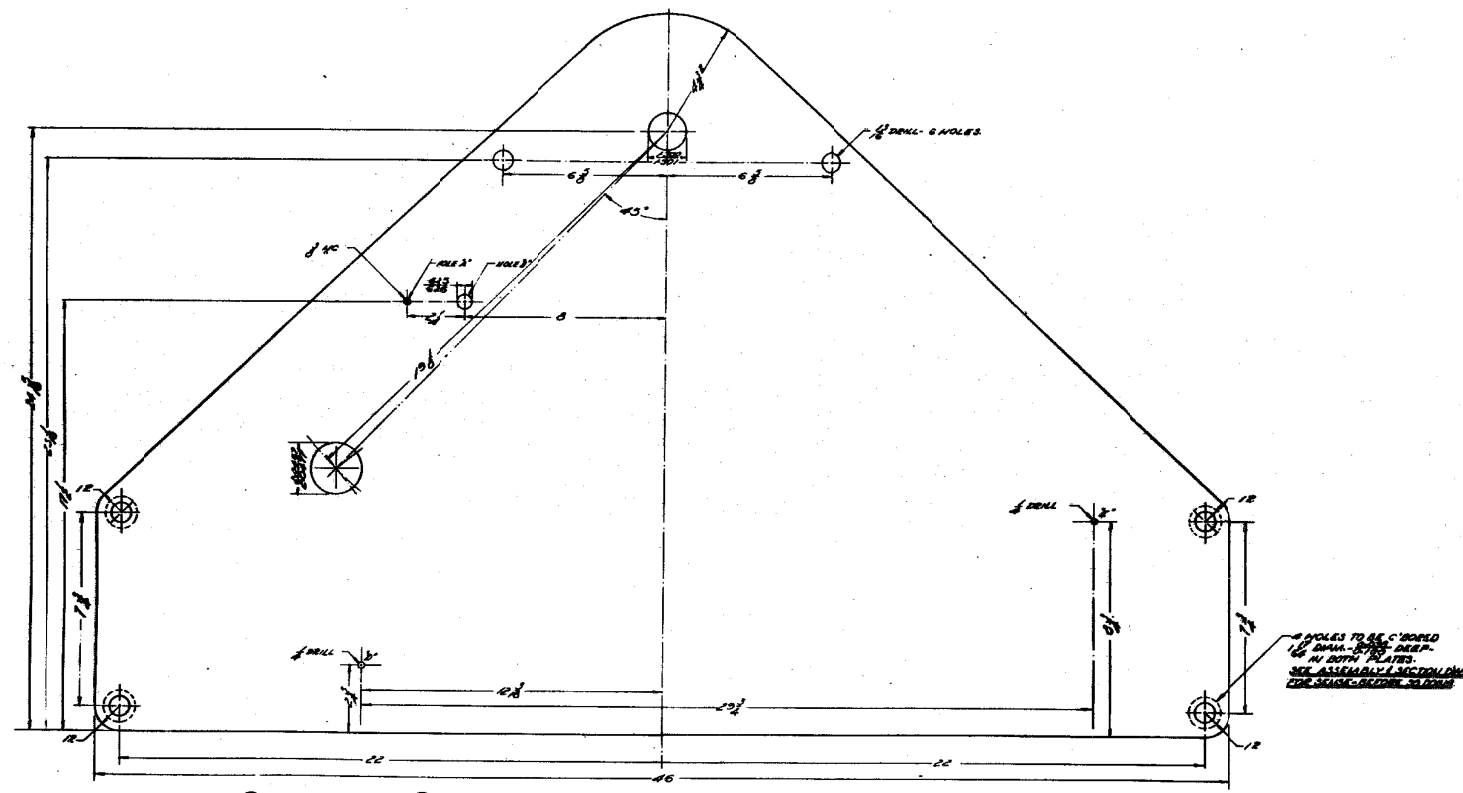
SIDE WEIGHT RACK

EQ 31



BOTTOM PLATE (1) AND TOP PLATE (9) 1 OF EACH REQ'D.

ALUMINUM - 2 PCES 3/8 × 30 × 46.

NOTE:

MATCH DRILL TEMPLATES (EQ. 3 & 5) TO "D" & "E" & DRILL 3/16 CLEARHOLES INDICATED.

HOLES MARKED "A" & "B" - FOR BOTTOM PLATE ONLY.

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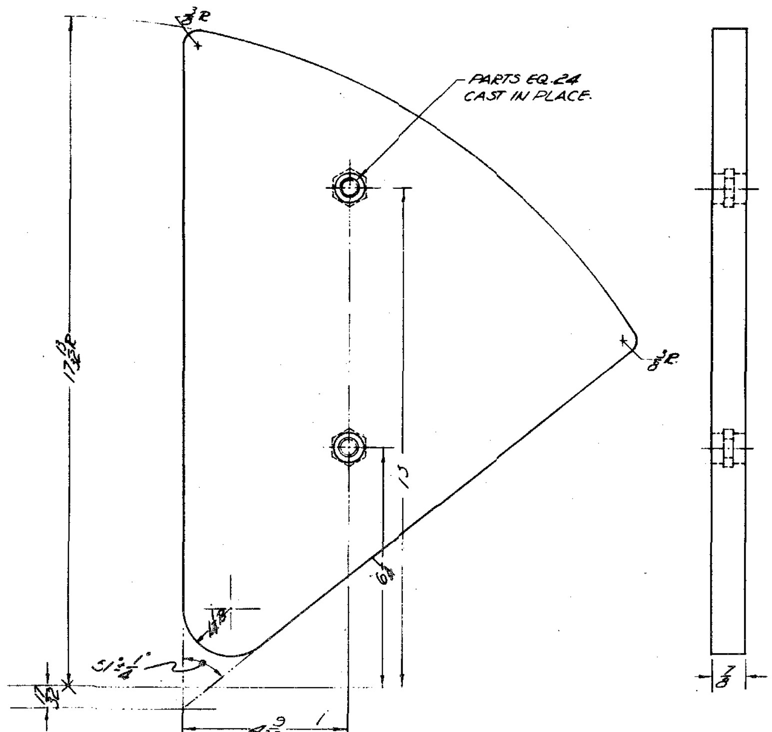
BOTTOM & TOP PLATES.

EQ. 1. & EQ. 3.



SIDE WEIGHTS
LEAD CASTING.

32

16 REQ'D.

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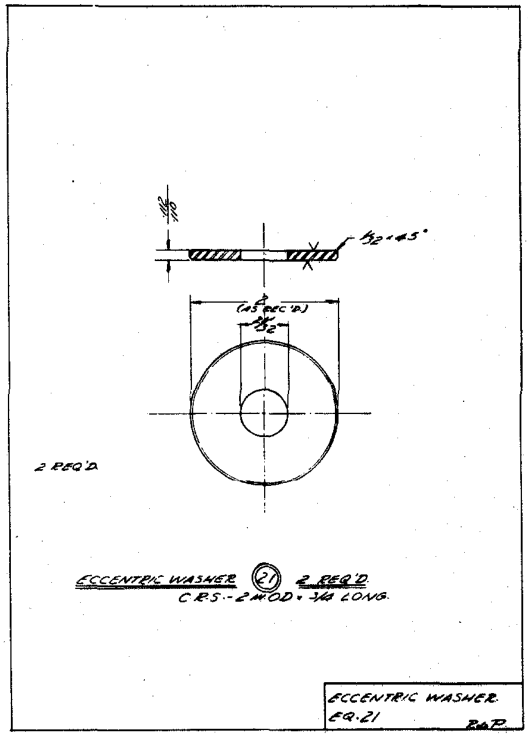
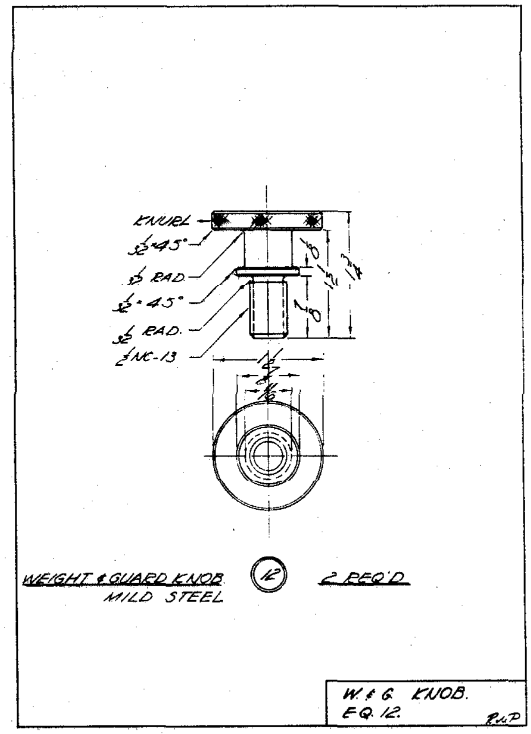
SIDE WEIGHTS.

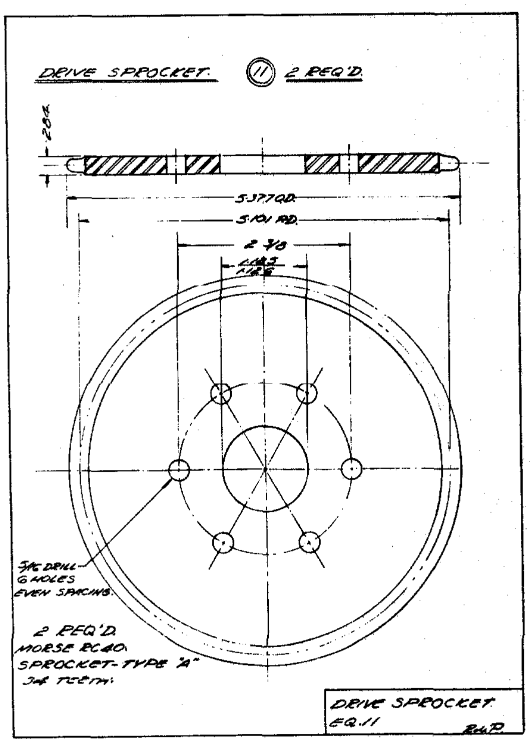
EQ 32



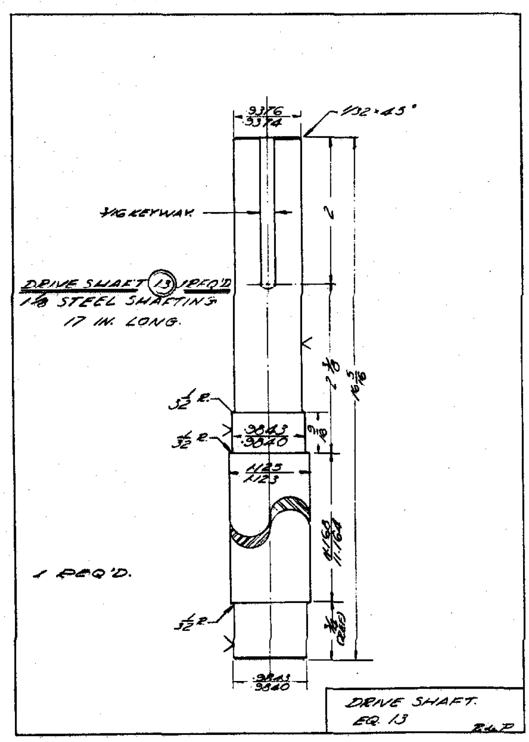
1/32 × 45°
2 REQ'D.
ECCENTRIC WASHER (21) 2 REQ'D.
C.R.S. - 2 IN. O.D. × 3/16 LONG.
ECCENTRIC WASHER
EQ. 21
R.&P.



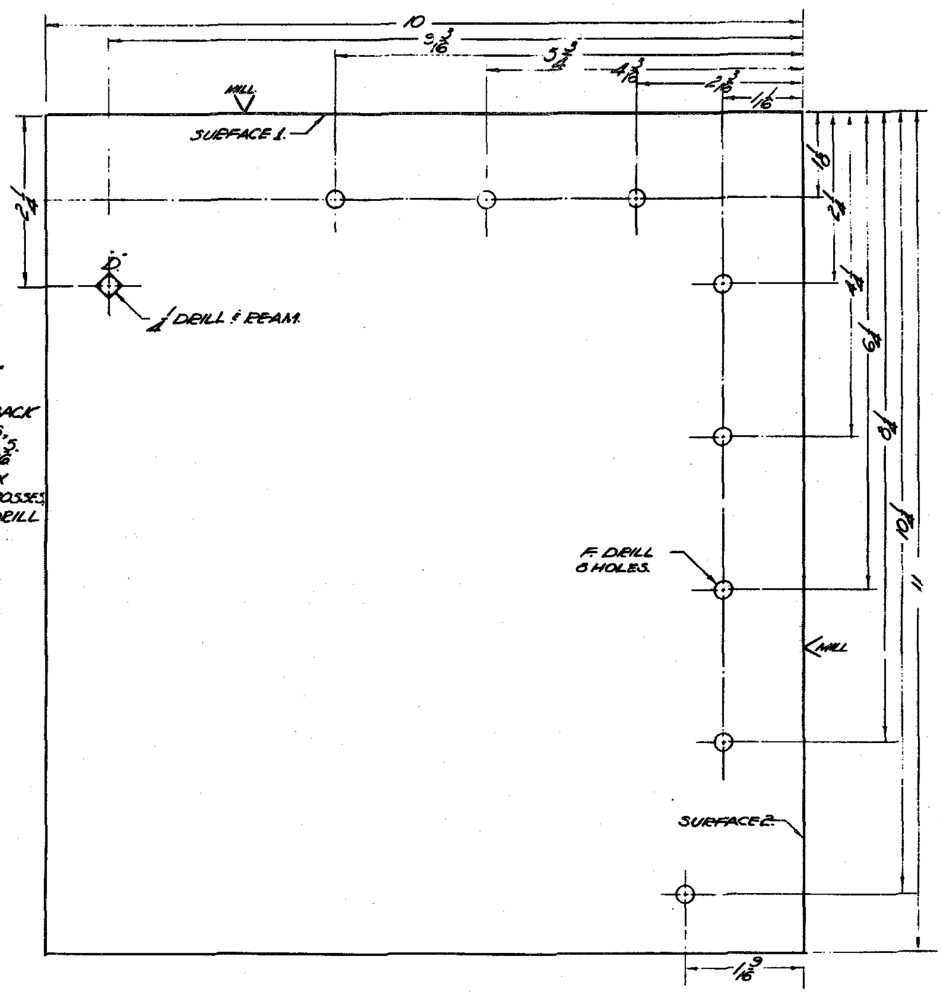
KNURL
1/32 × 45°
1/32 RAD.
1/32 × 45°
1/32 RAD.
1/2 NC-13
WEIGHT & GUARD KNOB (12) 2 REQ'D
MILD STEEL
W. & G. KNOB.
EQ. 12.
R.&P.



DRIVE SPROCKET. (11) 2 REQ'D.
5.377 O.D.
5.101 P.D.
2 7/8
5/16 DRILL
6 HOLES
EVEN SPACING.
2 REQ'D.
MORSE RC40
SPROCKET-TYPE "A"
34 TEETH.
DRIVE SPROCKET.
EQ. 11
R.&P.



1/32 × 45°
3/16 KEYWAY
DRIVE SHAFT (13) 1 REQ'D
1 1/8 STEEL SHAFTING
17 IN. LONG.
1/32 R.
1/32 R.
1 REQ'D.
1/32 R.
DRIVE SHAFT.
EQ. 13
R.&P.



NOTES.
1. MATCH DOWEL HOLE "D" WITH "D" OF TOP & BOTTOM PLATE, CLAMP WITH SURFACE 1 PARRELLEL TO BACK EDGE OF PLATE. F DRILL 8 HOLES, REMOVE TEMPLATE, & CLEAR WITH 5/16.
2. FOR TOP & BOTTOM OF TORQUE BOX ENDS, ALIGN SURFACE 2 WITH 2 BOSSES, SURFACE 1 WITH ONE, CLAMP, F DRILL 8 HOLES, REMOVE, & 5/16 NC 18 TAP THOSE HOLES.

DRILL TEMPLATE Nº 2 (33) 1 REQ'D
MATERIAL - 1/4 STEEL PL. 11 IN. × 10 IN.

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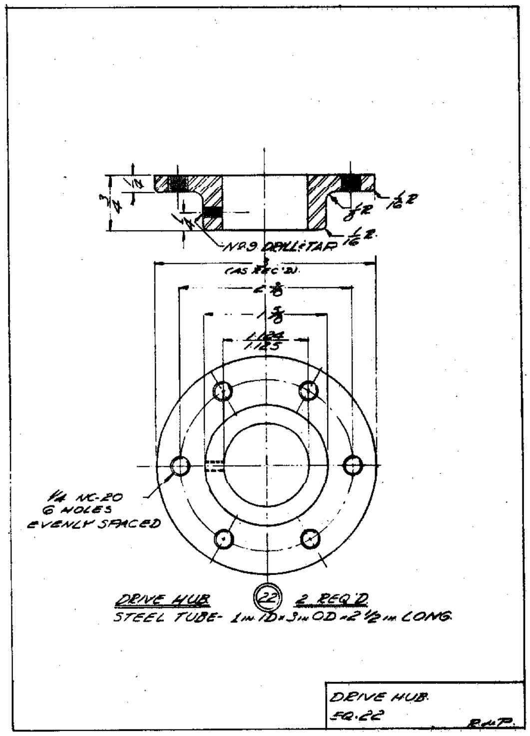
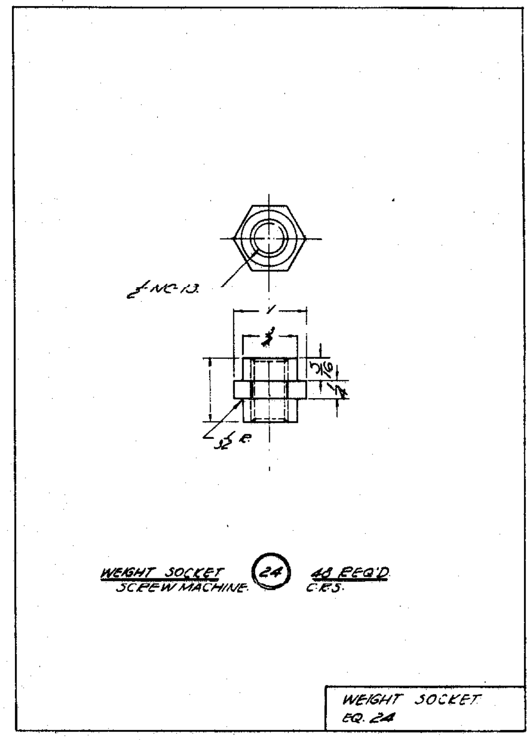
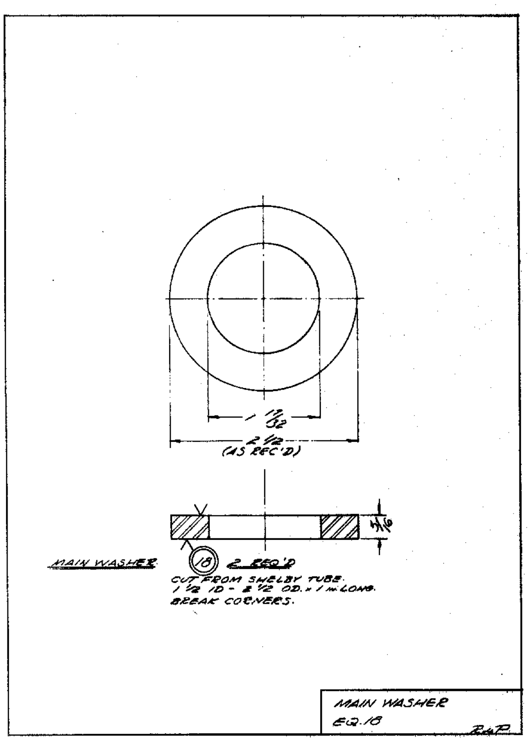
DRILL TEMPLATE Nº 2 (FOR TORQUE BOX END.)
EQ. 33
R.K.P.



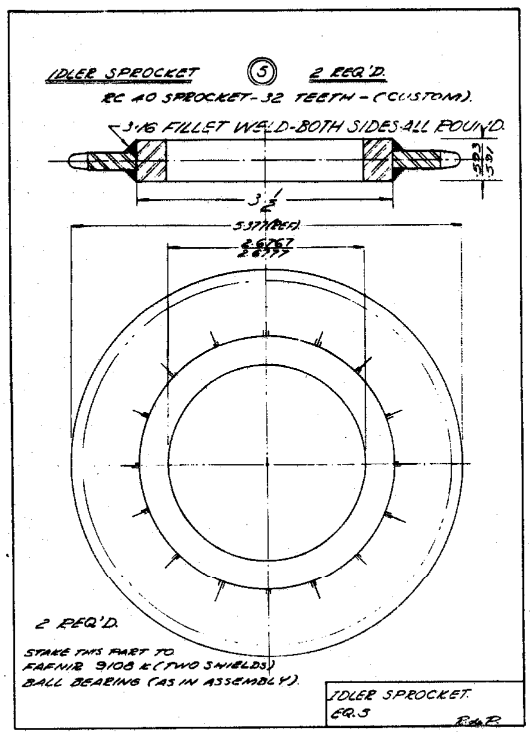
NO.9 DRILL & TAP
3 (AS REQ'D)
1/4 NC-20
6 HOLES
EVENLY SPACED
DRIVE HUB (22) 2 REQ'D.
STEEL TUBE- 1 in ID x 3 in OD x 2 1/2 in LONG.
DRIVE HUB
EQ.22
R&P.



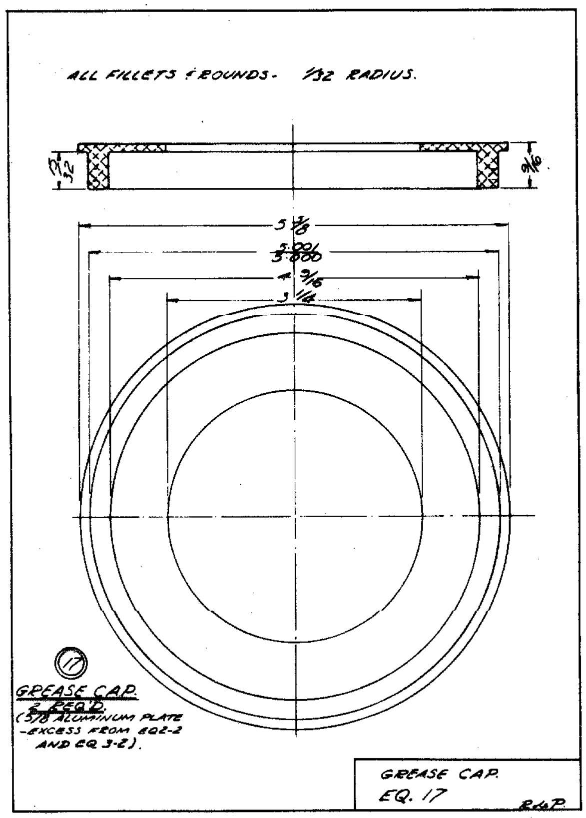
1/2 NC-13
WEIGHT SOCKET (24) 48 REQ'D.
SCREW MACHINE. C.R.S.
WEIGHT SOCKET
EQ. 24

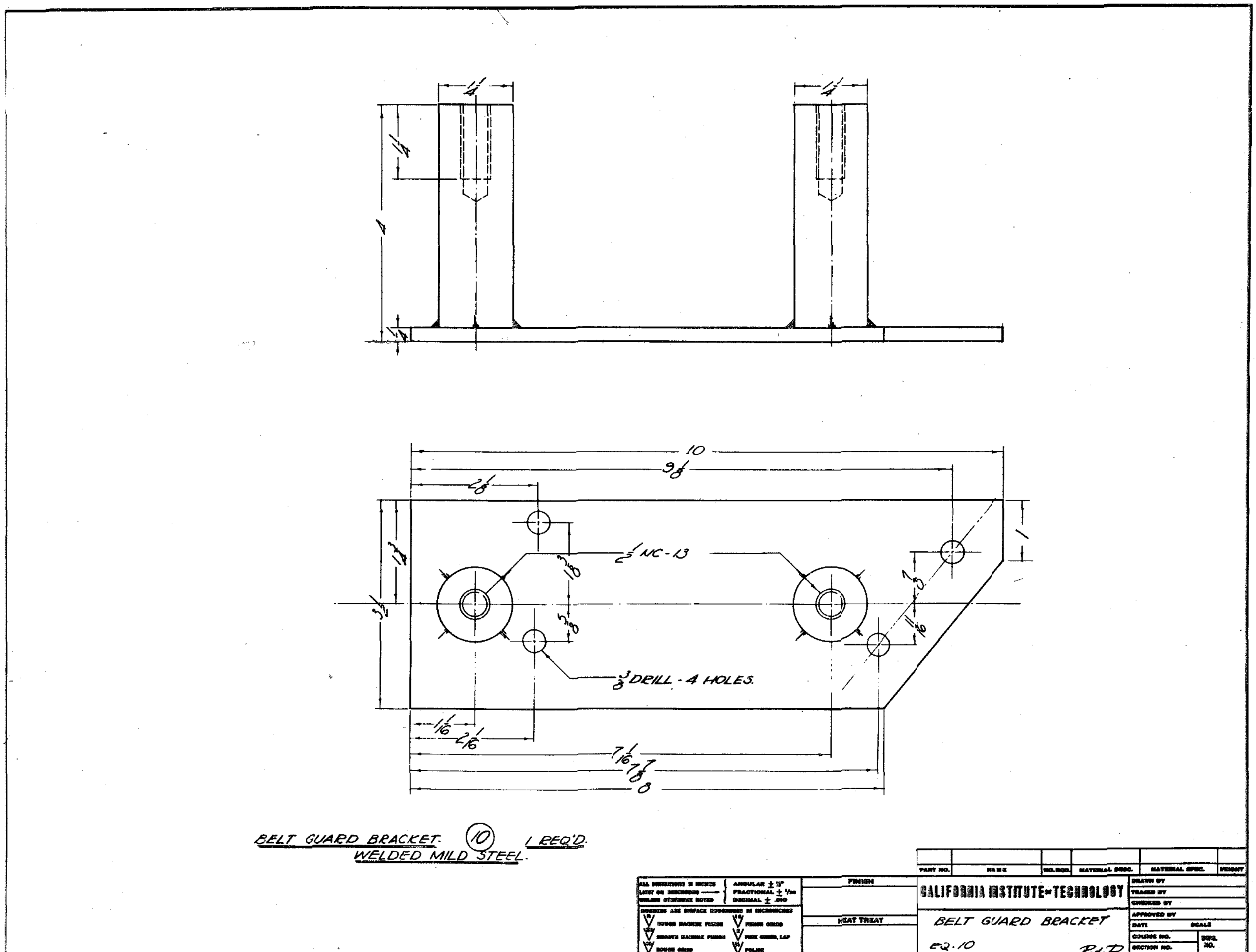


1 17/32
2 1/2 (AS REQ'D)
5/16
MAIN WASHER (18) 2 REQ'D.
CUT FROM SHELBY TUBE.
1 1/2 ID - 2 1/2 OD. x 1 in LONG.
BREAK CORNERS.
MAIN WASHER
EQ.18
R&P.



IDLER SPROCKET (5) 2 REQ'D.
RC 40 SPROCKET- 32 TEETH - (CUSTOM).
3/16 FILLET WELD-BOTH SIDES ALL ROUND.
3 1/2
5.377 (REF.)
2.6767
2.6777
2 REQ'D.
STAKE THIS PART TO
FAFNIR 9108 K (TWO SHIELDS)
BALL BEARING (AS IN ASSEMBLY).
IDLER SPROCKET
EQ.5
R&P.

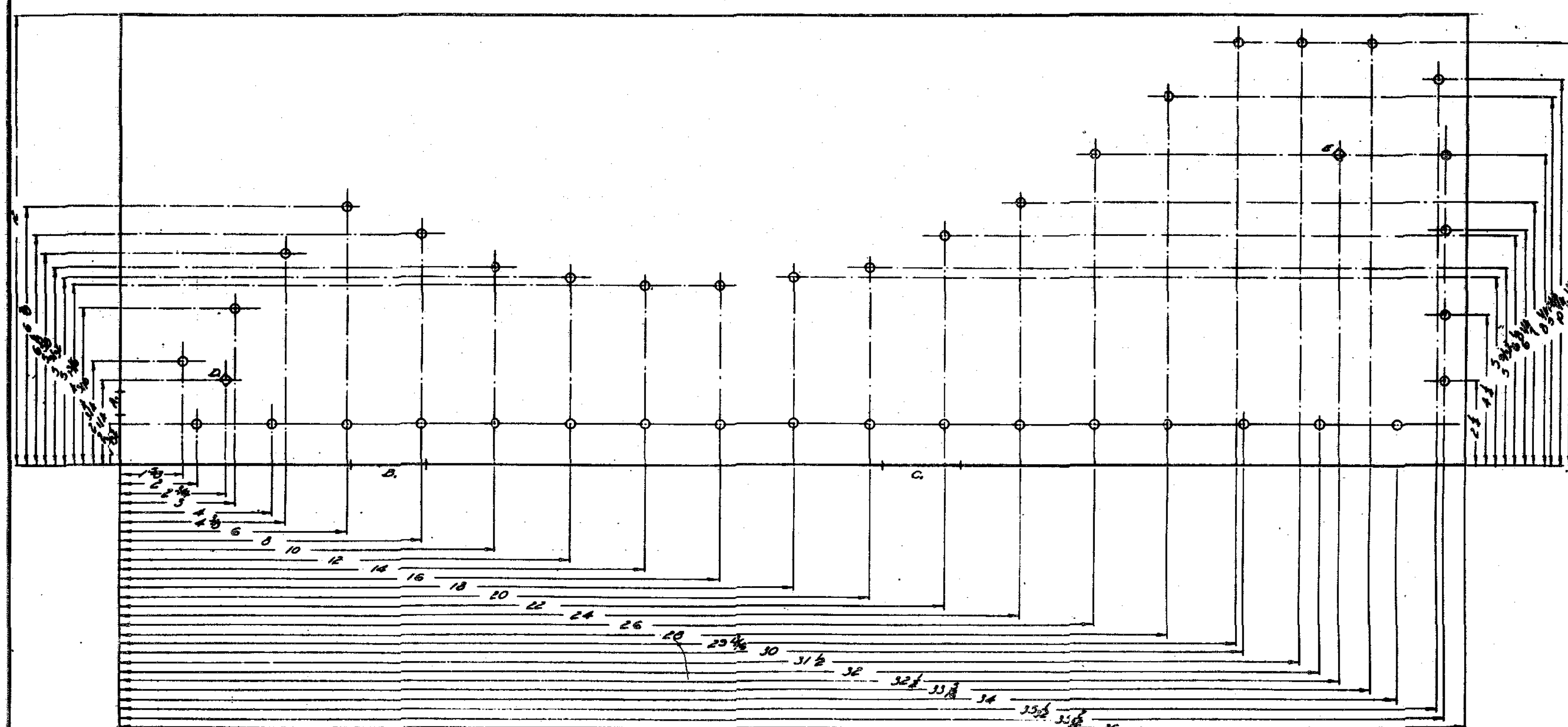

ALL FILLETS & ROUNDS - 1/32 RADIUS.
13/32
9/16
5 3/8
5.001
5.000
4 9/16
3 1/4
17
GREASE CAP.
2 REQ'D.
(5/8 ALUMINUM PLATE
-EXCESS FROM EQ2-2
AND EQ 3-2).
GREASE CAP.
EQ. 17
R&P.



1/4
1 1/4
4
10
9 3/8
2 3/8
1 3/4
3 1/2
1/2 NC-13
1 3/8
3/8 DRILL - 4 HOLES.
1
7/8
1 1/16
1 1/16
2 1/16
7 1/16
7 7/8
8
BELT GUARD BRACKET (10) 1 REQ'D.
WELDED MILD STEEL.
PART NO.
NAME
NO. REQD.
MATERIAL DESG.
MATERIAL SPEC.
WEIGHT
CALIFORNIA INSTITUTE of TECHNOLOGY
DRAWN BY
TRACED BY
CHECKED BY
APPROVED BY
DATE
SCALE
COURSE NO.
SECTION NO.
DWG. NO.
BELT GUARD BRACKET
E2-10
R.L.D.
FINISH
HEAT TREAT
ANGULAR ± 1/2°
FRACTIONAL ± 1/64
DECIMAL ± .010

◇ EQUIV. TO 1/4 DRILL & REAM.
○ EQUIV. TO "F" DRILL

1/4 IN. MILD STEEL PLATE



NOTE: TO BE USED FOR
(i) EQ. 6 - WITH CORRESPONDING A, B, C, FLUSH.
(ii) EQ. 1 & 9 - MATCH D & E & SEE B & C 1/2 IN. FROM PLATE EDGE.

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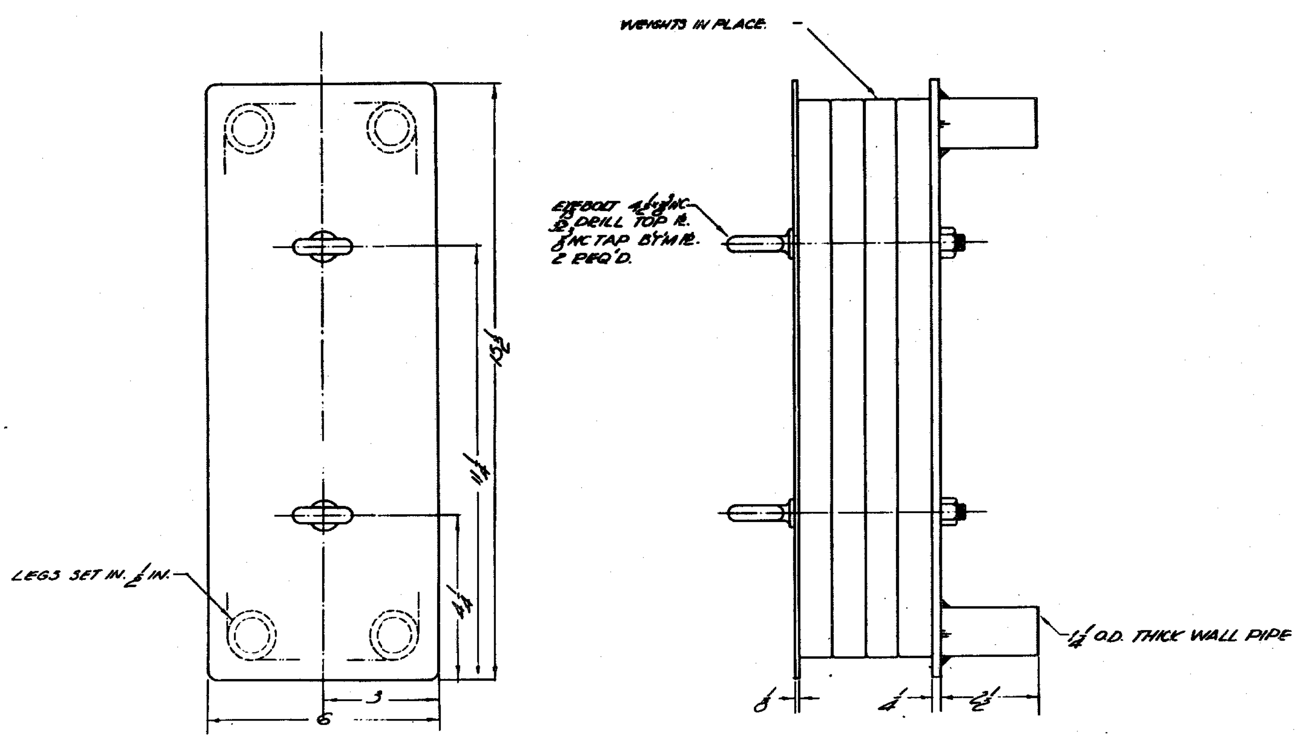
DRILL TEMPLATE No. 1

EQ. 35

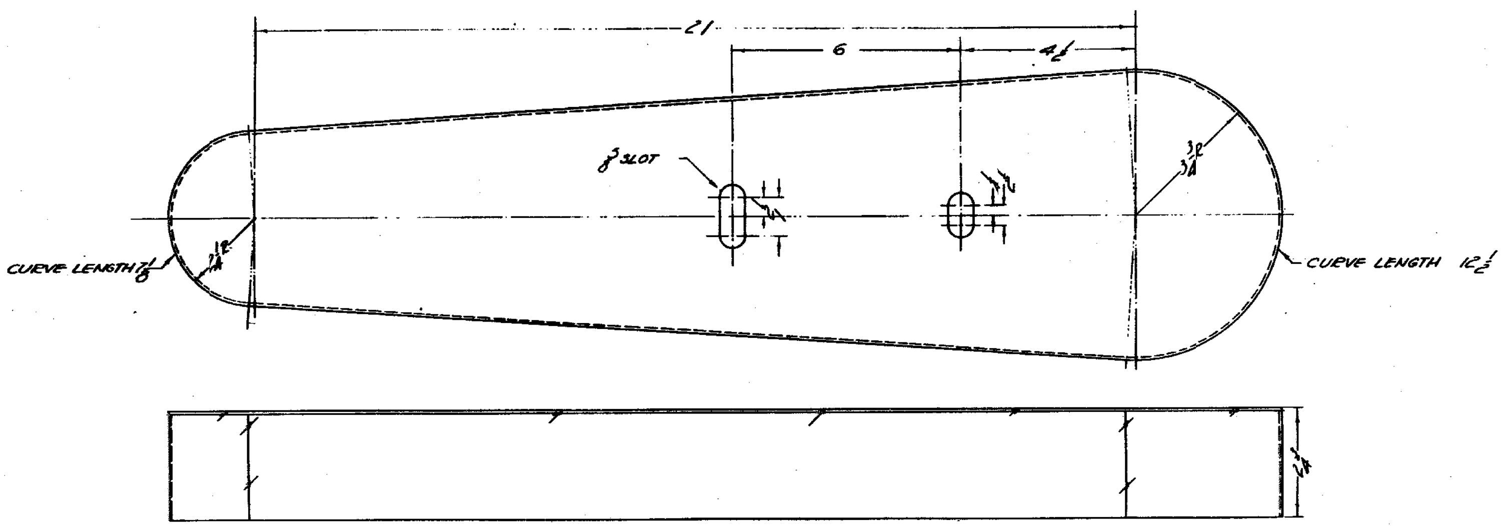
R.&P.



CENTRE WEIGHT RACK (34) 2 REQ'D.
MILD STEEL.

FINISH	CALIFORNIA INSTITUTE of TECHNOLOGY	DRAWN BY
HEAT TREAT	CENTRE WEIGHT RACK	CHECKED BY
	EQ. 34 R.A.P.	DATE

NOTE: CORNERS TO BE ROUNDED AFTER WELDING.



BELT GUARD (8) 1 REQ'D.
16 GA. MILD STEEL

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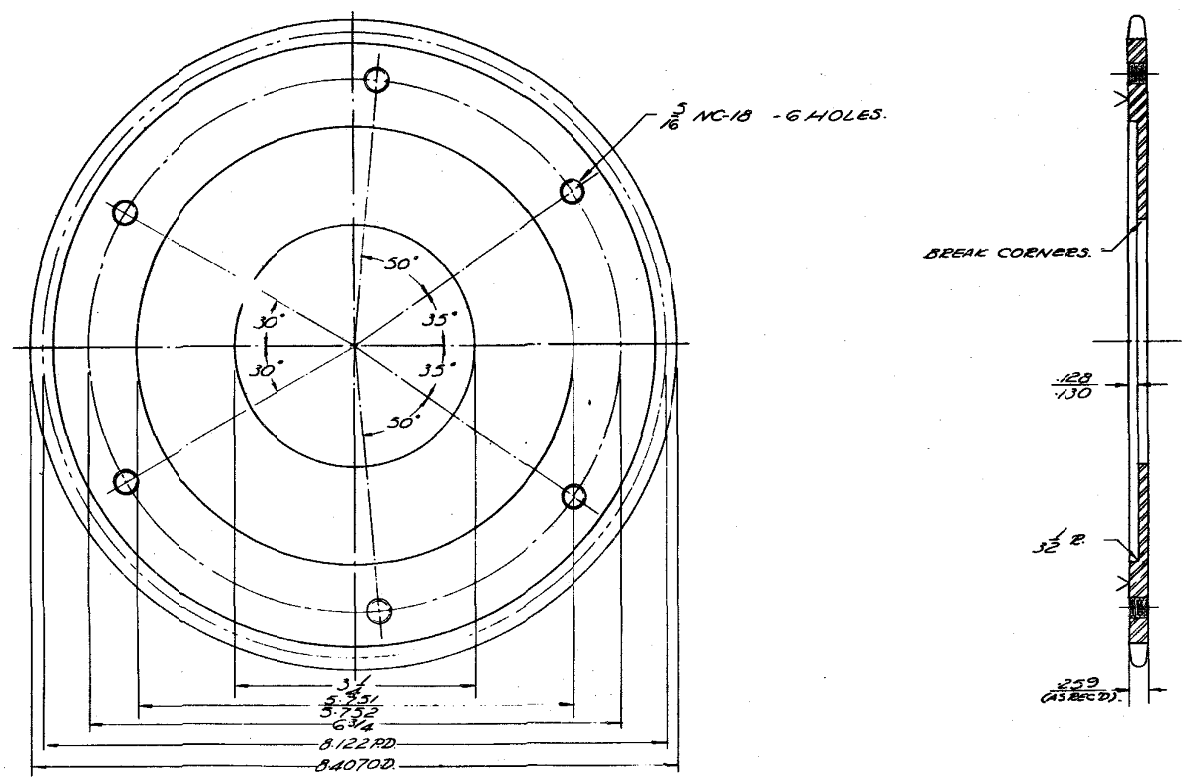
BELT GUARD

EQ. 8.

R.P.



BOX SPROCKET (15) 2 REQ'D.

MORSE SPROCKET - TYPE "A" - RC 40 - 51 TEETH.
(THIS PART LOCATES HOLES IN EQ 5-4 AT ASS'Y.)

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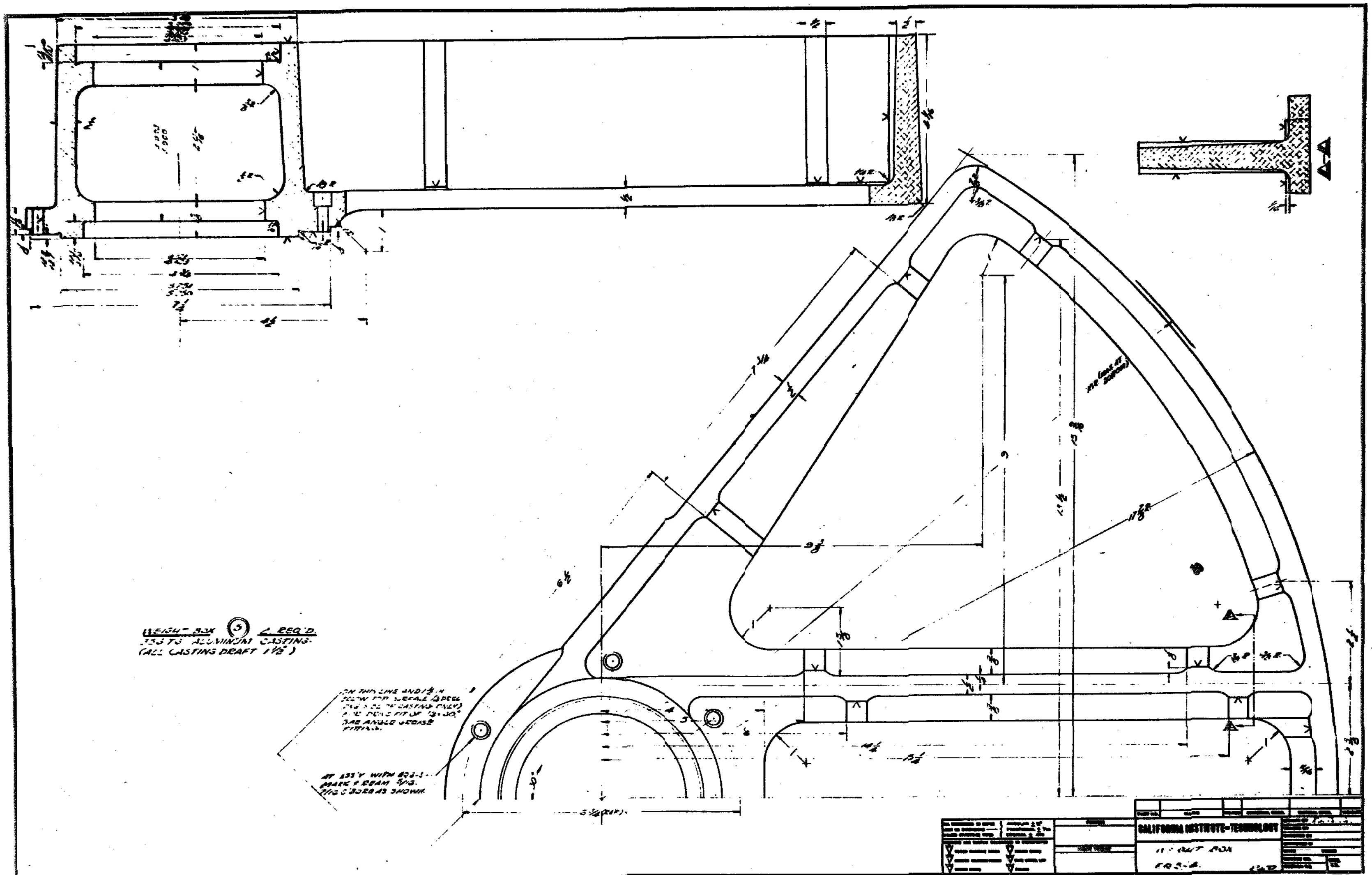
BOX SPROCKET.

EQ.15


A–A
ALUMINUM CASTING
(ALL CASTING DRAFT 1½°)
MARK & REAM 5/16
C'BORE AS SHOWN
CALIFORNIA INSTITUTE–TECHNOLOGY